VISUAL PERFORMANCE FOLLOWING HIGH INTENSITY FLASHES

NORMA D. MILLER

VINCENT M. KING

JOHN SCHOESSLER

JANUARY, 1968

The Ohio State University Research Foundation
Final Report, Contract AF-41(609)-3078, prepared for:
USAF School of Aerospace Medicine
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FOREWORD

This report was prepared by the Ohio State University Research Foundation under Contract No. AF-41(609)-3078 with the USAF School of Aerospace Medicine, Aerospace Medical Division, Brooks Air Force Base, Texas. Norma D. Miller, of the School of Optometry was the principal investigator. The project was initiated by the School of Aerospace Medicine, Brooks Air Force Base and was monitored initially by Major L. R. Loper. The latter phase of the work was monitored by Captain J. E. Hamilton. It is a pleasure to acknowledge the support and guidance provided by these two officers during the course of the work as well as the support given by Mr. Everet O. Richey, also of the School of Aerospace Medicine. Dr. Glenn A. Fry, Director of the School of Optometry, The Ohio State University, served as Senior Faculty Consultant during most of the experimental program. Much of the success of the work is due to his extraordinary ability in instrument design and to his willingness to carry on long discussions about the various phases of the work. This work represents the fourth phase of a continuing effort in the area of the visual effect of high intensity flashes. The work described in this report covers the research conducted during the period of 16 May 1966 through

15 May 1967 and was performed under Task 630103 and Program Element 6.16.46.01.D, Project 5710, Subtask 03.003, and was partially funded by the Defense Atomic Support Agency.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ABSTRACT

Three separate investigations into various areas of visual function at high levels of adaptation are reported. The reciprocity relationship between duration and intensity was studied for flashes of the order of 10^7 td·sec and for durations of 1.2 msec and 1.5 sec. There was approximately a 40% increase in recovery times for Sloan-Snellen test letters following the longer flashes.

The effect of varying the interval between two 250 μsec flashes on the subsequent recovery times was investigated. The interval between flashes was varied from zero to 1 msec in 100μsec increments. The total integrated luminous energy in the flashes was of the order of 10^7 td·sec. There was a statistically significant change in recovery time with the interval between flashes at the 5% level. The 700 μsec interval resulted in an 18% increase in recovery time compared with the zero interval for 130 mL targets. This is equivalent to more than doubling the energy in the zero interval or 500 μsec duration case.

In the third portion of the work, increment thresholds were measured for 45' monochromatic flashes superimposed on a 10° white light background of various illuminance levels from 10 td

to 5×10^4 td. At the higher levels, marked notches appear in the sensitivity function at 570 nm and 470 nm as previously reported by Sperling. Analysis of the results shows a striking similarity with the purity threshold curve and with MacAdam's ellipse for the white point of the chromaticity diagram.

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VISUAL RECOVERY FROM HIGH INTENSITY FLASHES

INTRODUCTION

The human visual system is very sensitive to small differences in luminances within the field of view. The normal individual will perceive a relatively small area differing by only two percent in luminance from the surround level if he is adapted to the surround level. If the average level of illumination in a visual field is suddenly altered, there is a period of changing sensitivity until the new level of adaptation is reached. Even relatively small changes in illumination level result in a period of adaptation. Several studies[1-3] of the sensitivity of the eye during the transient period of adaptation have shown that there are two basic mechanisms responsible for the rapidly changing sensitivity. There is a neural effect, which is short lived and a photochemical effect which persists for a longer period of time.

Flashblindness is different in degree, not in kind, from any dark adaptation following exposure to increased light levels. In fact, it would be difficult to define precisely what is meant by flashblindness. Even the common experience of glancing out of the window at the bright sky and then looking down at work on the desk results in a short period of reduced visual sensitivity

or in flashblindness. However, as the total amount of light flux entering the eye during a flash exposure is increased, a point is reached where a vivid afterimage of the flash source is perceived following the exposure. One is aware of the rapid fading of the afterimage during the period of readaptation to the preflash illumination level. Extensive work over the last few decades has confirmed that the afterimage is photochemical in origin.

Craik[4] was probably the first to demonstrate conclusively that the afterimage was produced by events at the retinal level. He temporarily blinded the eye by pressure on the globe, preventing the transmission of neural signals from the retina. While the pressure was applied, the eye was subjected to a bright flash which the subject could not preceive; but, when the pressure was removed and the normal neural transmission restored, the afterimage was perceived. Subsequently, Rushton[5, 6] performed a series of experiments in which he measured the bleaching of the retinal photopigments in the living human eye and correlated the regeneration of the pigments with the change in increment thresholds during dark adaptation.

In military operations, where personnel may be subjected to intense flashes of light, the problem of flashblindness takes on particular significance. It is not enough to know academically

that the flash has bleached the retinal pigments and caused a veiling bright afterimage to appear, but it is also necessary to know how much and how soon one can see after the exposure. It takes longer to discriminate fine detail than to recognize gross outlines. Therefore, one of the parameters of visual recovery is the size of the detail subtended by the visual task.[7] Another important parameter in recovery time is the total energy received by the retina during the flash.[8] Previous work in this laboratory has shown that the rate of delivery of the energy in a flash is also a parameter of recovery time.[8] The retinal position and the angular size of the flash received are additional parameters. The number of variables to be investigated in order to adequately describe visual recovery during flashblindness makes the task formidable. The one hope in solving such a complex problem is to look at the basic mechanisms in an effort to develop a predictive model for estimating how much and how soon one can see.

For several years we have investigated the problems of visual recovery following brief, high intensity flashes. The primary effort has been directed toward an understanding of the mechanisms underlying flashblindness in order to reduce the burden of experimental determination of the effects of each of the variables. The previous work has shown a simple relationship

to exist between recovery times for any target and the instantaneous brightness of the afterimage.[9] We have found that the rise in increment threshold following an intense flash of light depends upon the instantaneous brightness of the afterimage in precisely the same manner as an external field of the same subjective brightness. It was found[10] that the instantaneous brightness of the afterimage was related to the time following the flash as a power function with an exponent of -3.

For military operations there is a need to predict the brightness of the afterimage at a given time following different types of flashes. If a reciprocity relationship between intensity and time in the flash holds, it is merely necessary to measure the recovery time for different flash energies for any flash duration. On the basis of absolute threshold studies, one might predict that the reciprocity relationship does hold. It has been investigated over a wide range of stimulus durations at threshold and no failure in the relationship was found.[11] However, flash photolysis in solutions of retinal pigments indicate a distinct reciprocity failure. Williams investigated the phenomenon thoroughly and suggested a theoretical model to explain the reduction in flash effectivness for equal energies when the durations were very short.[12] Psychophysical experiments in this laboratory also showed a reciprocity

failure between time and intensity for very short flashes of light. Equal energy flashes with durations from 0.5 to 1.5 msec were shown to produce different recovery times with the short flashes resulting in shorter recovery times.

A portion of the work undertaken during this report period was directed toward a better understanding of the reciprocity relationship. One investigation was concerned with the comparison of the effect of equal energy flashes of durations in the millisecond and the full second range on the subsequent recovery times. A second investigation was concerned with the effect on recovery times of presenting brief double flashes with various time intervals between the flashes. The separate flashes were 250 μsec in duration and the intervals between the two ranged from 0 to 1 msec.

A second portion of the research was directed toward investigating the increment thresholds for different wavelengths of light for different adaptation levels of the surround. Earlier work in this laboratory indicated that the instantaneous afterimage following a flash acted in precisely the same way as an external field of the same subjective brightness in respect to the increment threshold for white light recovery targets. The color sensitivity research was undertaken as the first phase in a longer research

program to determine if the color sensitivity at any instant following an intense flash is the same as that produced by an equivalently bright external field.

This report is presented in three main subdivisions corresponding to the three major research efforts during the report period as follows:

PART I

The Effect of the Rate of Delivery of Flash Energy on Recovery Time, by Norma D. Miller.

PART II

Recovery Times Following Brief Double Flashes with Various Intervals During the Flashes, by Norma D. Miller and Vincent M. King.

PART III

Visual Sensitivity for Various Wavelengths as a Function of Adaptation Level, by Norma D. Miller, Vincent M. King, and John Schoessler.

I. THE EFFECT OF THE RATE OF DELIVERY OF FLASH ENERGY ON RECOVERY TIMES

Norma D. Miller

1. INTRODUCTION

Psychophysical studies have shown that a failure in the reciprocity relation between intensity and duration occurs for flashes in the submillisecond range of durations.[8] Hagins[13] measured the amount of bleaching of the photopigment in albino rabbit eyes and found that not more than one half of the pigment could be bleached with flashes of one millisecond duration compared with much longer flashes of the order of one second. Due to the commonly accepted view that the instantaneous brightness of the afterimage is related to the amount of unregenerated photopigment, one would expect to find longer recovery times for flashes of the order of one second compared with those in the millisecond range.

The present investigation was undertaken to measure the recovery times of flashes differing by a factor of greater than 1000 in their duration. Inasmuch as the peak radiance of the xenon discharge tube is at least 100 times greater than that of the tungsten ribbon filament lamp, it was possible to provide flashes

of the order of 1 msec by the xenon flash tube and compare them for the same energy levels with flashes of approximately a second produced by the tungsten lamp.

2. APPARATUS

The basic apparatus used in the research was the same as that used in former flashblindness studies and is fully described elsewhere.[14] Figure 1 shows a schematic diagram of the optical components and indicates the few modifications made in order to produce the different duration flashes. A cardboard sector disc just behind the plane of the aperture A_2 was driven at 1780 rpm. A small sector was removed from the disc to provide an exposure of 1.1 msec. The discharge tube was triggered by a slit cut near the center of the disc which exposed a rapid response photodiode. An auxiliary hand-operated shutter covered the photodiode until it was time to trigger the discharge tube. An additional cardboard sector disc was provided at the entrance aperture A_1. This was a small disc driven by a 20 rpm motor. The size of the sector could be modified to provide a flash from the tungsten lamp S_2, equal in energy to that from the xenon discharge tube. A first surface mirror was mounted at 45° in front of the entrance aperture A_1 to admit the light from the

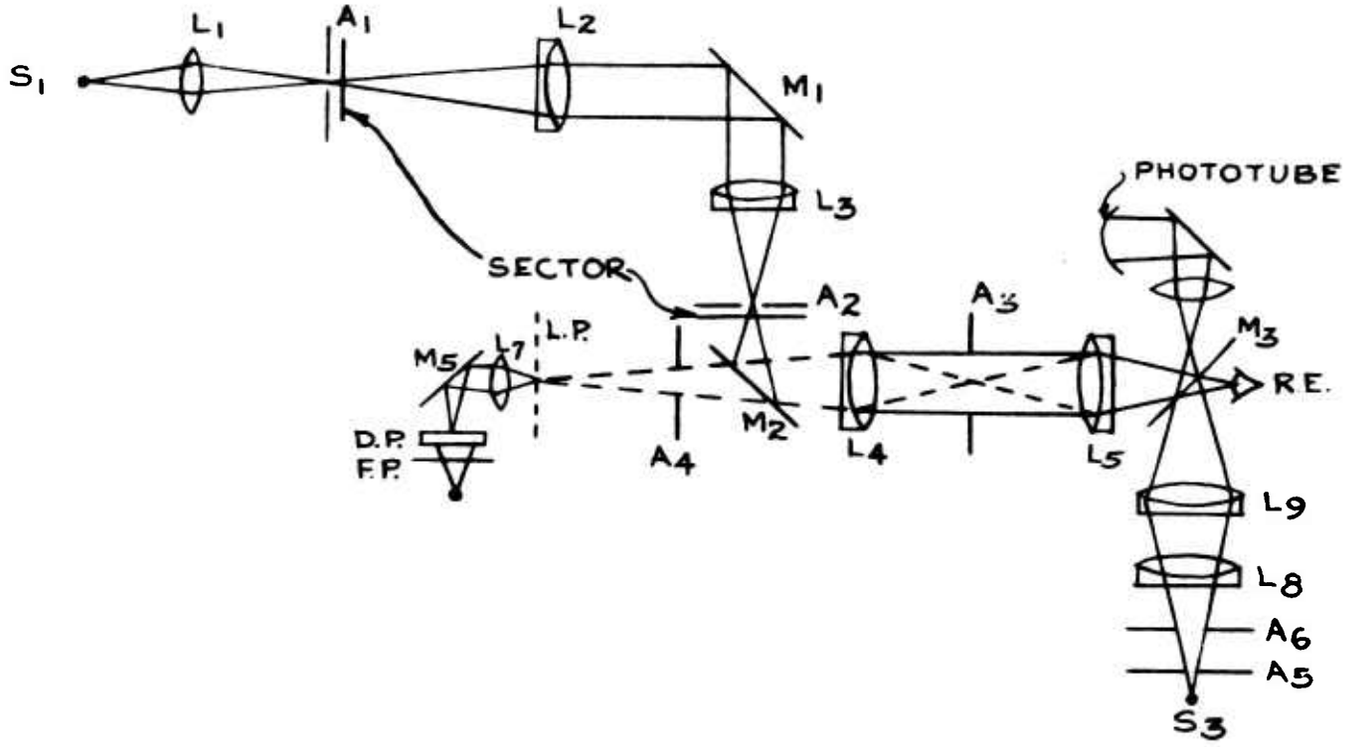

Figure 1. Schematic diagram of the flashblindness apparatus.

tungsten lamp. The mirror mount was machined in such a way that it could be quickly and accurately slipped into position to shift from the xenon to the tungsten light.

The source radiances were calibrated by comparing them through a 550 nm interference filter. The tungsten lamp was an 18 amp ribbon filament lamp carefully standardized and operated with carefully controlled current throughout the experiments. The lamp had a color temperature of 3000°K; the filament luminance was approximately 1000 cd/cm^2. The comparison of the two sources was made through the 550 nm interference filter to circumvent the problems due to the difference in the spectral characteristics of the two sources. A phototube was placed behind the exit pupil of the total optical system to receive the flux passing through the Maxwellian beam normally focused at the entrance pupil of the subject's eye. Additional neutral density filters were placed in the light beam from the flash tube in order to provide the same order of magnitude of phototube signal for the two sources. The phototube signals were displayed on a Tektronix oscilloscope and photographed. The relative heights of the two traces plus the calibration of the neutral density attenuating filters in the xenon beam gave the relative radiances for the two sources for a narrow band of wavelengths centered about 550 nm.

Previous spectral calibration of the xenon discharge source permitted calculation of the total luminance of the xenon from the above data. The xenon discharge was approximately 1400 times higher in luminance than the ribbon filament lamp. The calibration was repeated each morning before any experimental sessions were run.

The Maxwellian beam at the entrance pupil to the subject's eye was 2.5 x 3.5 mm. It was necessary to position the eye relative to the axis of the optical system with considerable precision to insure that the entire Maxwellian beam would enter the pupil for all flashes. This was accomplished by means of a wax dental impression clamped firmly in an apparatus which provided movement up and down, right and left, and in and out. Alignment of the subject's right eye with the apparatus was done by placing a pinhole pupil in the apparatus about 15 mm in front of the cornea. This pupil and etched cross hairs, which were placed in the field stop A_3, were on the optical axis of the system. The subject moved his head until the shadow of his own pupil was concentric with the cross hairs. By means of a sighting device, the experimenter positioned the subject fore and aft so that the apex of the subject's cornea was 3 mm in front of the focal point of Lens L_5. Figure 2 shows the clamping and aligning apparatus with the wax dental impression in place.

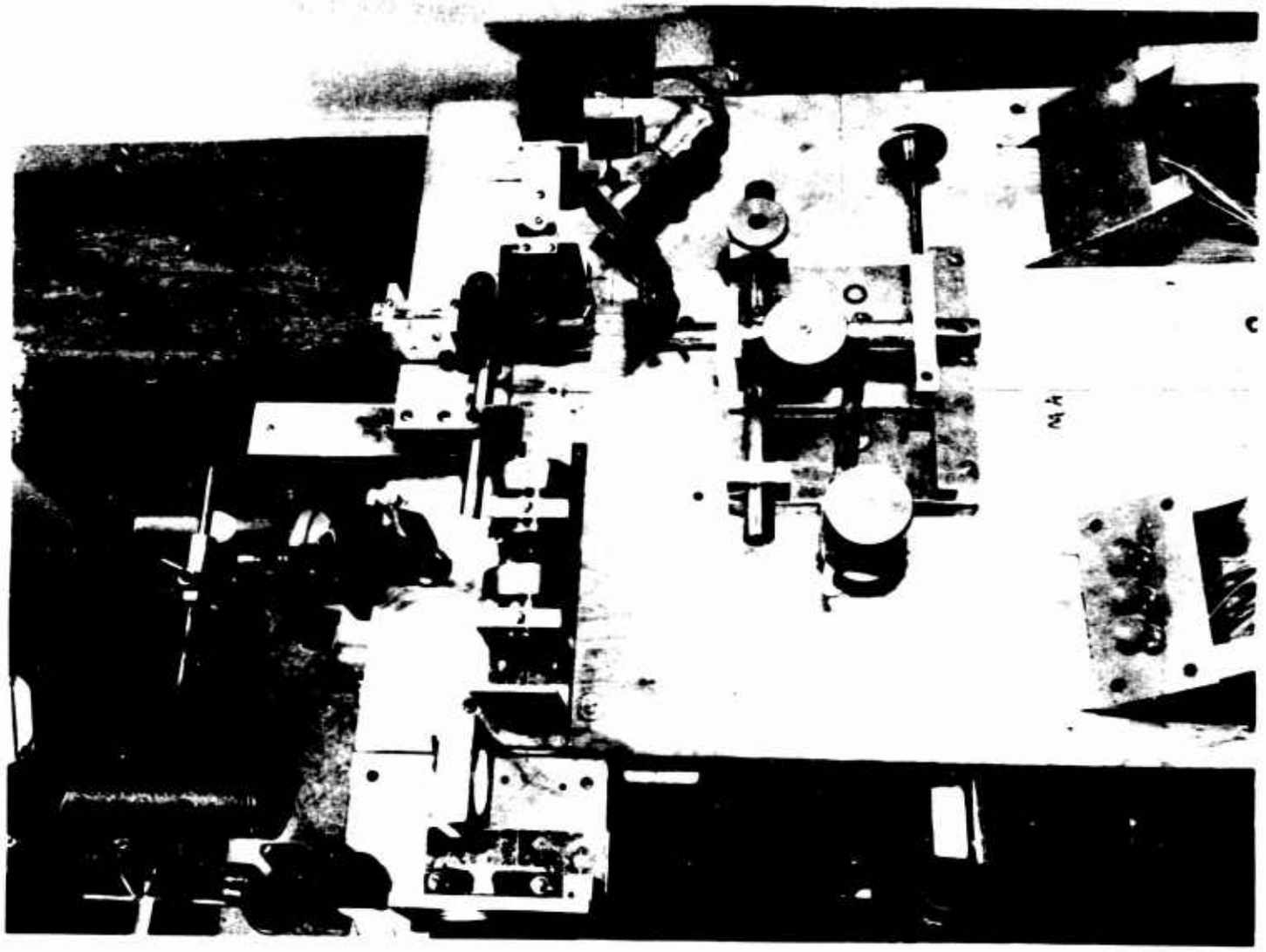

Figure 2. Photograph from subject's end of apparatus showing the bite-bar alignment device and the sighting device for positioning the subject.

The fixation direction was controlled by presenting an incomplete set of cross hairs into the field stop A_3 by means of a beam splitter, M_3. The cross hairs were positioned so that the imagined point of intersection of the lines fell at the center of the cross hairs at aperture A_3 and at the center of the recovery letter. A red gelatin filter was placed behind the fixation lines; the brightness of the lines was adjusted by the subject before the experiment by means of a Variac controlling the current to the tungsten filament source S_3.

Sloan-Snellen letters subtending 20.4 min of arc were used for the recovery targets. The recovery times for nine luminance levels of the Sloan-Snellen letters were measured following each flash of each series. The luminance levels could be controlled by filters in an automatically positioned filter wheel. The brightest letter was in the field of view within one second following the flash presentations. As soon as the subject correctly identified the letter, the time was automatically recorded and the target luminance reduced to the next level by rotating the filter wheel to the next filter density. The neutral density filters used in the filter wheel of the test letter system were calibrated on a Leeds and Northrup photometer bench. The filters were Eastman-Kodak 96 Wratten gelatin filters.

The luminance of the unfiltered test letter image in the plane of the field stop was measured with a Macbeth Illuminometer. An auxiliary lens was attached to the illuminometer to focus the small patch of light in the plane of the field stop onto the exit pupil of the instrument. The rear stop of the illuminometer was replaced by a smaller diameter aperture to insure that the light from the letter beam completely covered the exit pupil. The clear area of the unfiltered letters had a luminance of 130 mL when the tungsten lamp source was operated at 16 amps.

3. EXPERIMENTAL PROCEDURE

Four young male subjects participated in the experimental sessions. Each subject had been tested thoroughly for visual acuity, visual fields and color discriminations. All subjects had at least 20/20 visual acuity.

In the first experiment, flash durations of 1.1 msec and 1.5 seconds were used. The short duration flashes were produced by the xenon discharge lamp and the long duration flashes by a standard tungsten ribbon filament lamp. A 555 nm interference filter was placed in the flash beam for both sources. The total integrated luminous energy for the two flash durations was 2.6×10^6 td·sec. Five flashes of each duration were presented

during one experimental session. Six minutes elapsed between flash presentations. The two flash durations were independently randomized for each subject. The flash energies were monitored at each presentation and were held within $\pm$ 5% of the 2.6×10^6 td·sec value. If any individual flash varied more than 5% from the established level, the recovery data for that flash was discarded and that flash duration was repeated at the end of the series.

A second experiment was performed to determine the equivalent neutral density of the 555 nm interference filter for the xenon and tungsten sources. The equivalent density was calculated from the spectral distribution of the two sources and the spectral transmittance of the interference filter. The calculated values were 1.0 density for xenon and 1.1 for tungsten at 3000° color temperature. As a check on the calculations, a visual determination of the density was undertaken by comparing the recovery times for flashes filtered through 0.9 and 1.2 neutral density filters with recovery times for similar flashes filtered through the 555 nm filter.

The flash durations were 700 μsec for the xenon source and 1.0 sec for the tungsten source. The integrated luminous energy for the flashes for the two sources was equated for the 555 nm filter. Each subject received four flashes through each of the

three filters for both sources. The mean recovery times for all subjects for all trials for one flash condition were used to compare the effective flash energy through the 555 nm filter with that through the neutral filters.

In the third experiment, the equivalent density found in the second experiment was used to adjust the total spectral output of the two sources for equal luminous energy flashes based on the comparison at 550 nm. In each experimental session each subject received five flashes of 1.2 msec duration from the xenon source and 1.5 sec duration from the tungsten source. The order of the flashes was independently randomized for each subject. The total luminous energy per flash for each of the sources was 2.6×10^7 td·sec.

4. EXPERIMENTAL RESULTS

The results of the first experiment are shown in Table I. The group means of recovery times for the four subjects for each letter luminance is shown in columns 2 and 3 of the table for the two different flash sources. In all instances the recovery time for the 1.5 sec duration flash was considerably longer than that for the 1.1 msec duration in spite of the fact that there

Table I. Means of recovery times for four subjects for 20.4' Sloan-Snellen letters following 2.6×10^6 td·sec flashes of a narrow band of wavelengths centered about 550 nm.

Letter B	Mean recovery (sec)		
(ml)	1.5 sec duration	1.1 msec duration	1.5 sec/1.1 msec
64.60	5.24	3.69	1.460
5.47	8.32	5.93	1.402
0.98	13.78	9.54	1.445
0.13	18.47	12.48	1.481
0.081	23.62	15.64	1.511
0.059	34.97	22.25	1.570
0.046	45.50	31.33	1.452
0.031	59.63	39.33	1.518
0.014	72.05	48.68	1.479

as the same integrated energy per flash. Inasmuch as the 555 nm interference filter is a very narrow band pass filter it is impossible that the difference in spectral distribution for the two sources could introduce an artifact into the comparison of the two durations. The ratio of the recovery time of the 1.5 sec flash compared to the 1.1 msec flash is recorded in column 4 of Table 1. The mean ratio for all luminance levels for the four subjects was 1.48.

A similar comparison between the recovery times for the 700 μsec duration flashes is shown in Table II. The data are the results of one part of the second experiment using the flashes filtered through the 555 nm filter. The total integrated luminous energy for the tungsten and the xenon flashes were carefully matched by means of the phototube signal displayed on the oscilloscope as described in the Apparatus section. Again, the possibility of spectral distribution influencing the recovery time has been ruled out by the use of the narrow band pass filter. The mean recovery times for four flashes of each of the two durations for the four subjects are recorded in columns 2 and 3 of Table II. The ratio of the recovery time from the 1 sec flash to that of the 700 μsec flash is listed in column 4 of that table. The mean ratio for all letter luminances and all subjects was 1.454. The

Table II. Means of recovery times for four subjects for 20.4' Sloan-Snellen letters following 1.7×10^6 td·sec flashes of a narrow band of wavelengths centered about 550 nm .

Letter B	Mean recovery times (sec)		
(ml)	1.0 sec	700 μsec	$\frac{1.0 \text{ sec}}{700 \text{ μsec}}$
32.40	4.37	2.95	1.482
2.69	6.94	5.12	1.355
0.49	10.40	7.78	1.338
0.14	14.47	10.33	1.400
0.066	18.97	13.47	1.410
0.041	30.50	19.20	1.589
0.030	44.45	27.70	1.605

two separate determinations of the influence on recovery time of the longer duration flashes are in excellent agreement. The first experiment indicated a 48% increase in recovery time for the 1.5 sec duration flash compared with the 1.1 msec duration, and the second experiment showed a 45% increase for the 1sec duration compared with the 700 μsec duration.

The mean recovery times for the four subjects for 1 sec duration tungsten flashes filtered through the two different neutral densities and the 555 nm interference filter are shown in Table III. The mean ratio of the recovery times for tungsten light filtered through a 0.9 neutral density compared with filtering through the 1.2 neutral density was 1.407 or 41% increase in recovery time with a two times increase in the energy per flash. The mean ratio of recovery times from the tungsten filter through the 555 nm filter compared with the 1.2 neutral density filter was 1.092. This results in an effective neutral density of 1.12 for the 555 nm interference filter with tungsten light.

The mean recovery times for the 700 μsec xenon flashes filtered through 0.9 and 1.2 neutral densities and the 555 nm interference filter are shown in Table IV. The mean ratio of the recovery times for the 0.9 versus the 1.2 neutral density filter was 1.22 or a 22% increase in recovery time for a two times

Table III. Determination of the equivalent neutral density of the 555 nm interference filter by comparing the recovery times for 1.0 sec tungsten flashes filtered through 0.9 and 1.2 neutral densities and the interference filter.

Letter B	Recovery times (sec)			Ratios	
(ml)	0.9 N.D.	1.2 N.D.	555 mμ	0.9 N.D. / 1.2 N.D.	555 mμ / 1.2 N.D.
32.40	5.39	4.50	4.37	1.210	0.974
2.69	8.33	7.23	6.94	1.150	0.960
0.49	12.35	9.80	10.40	1.260	1.062
0.14	17.74	12.53	14.47	1.415	1.155
0.066	26.44	17.37	18.97	1.523	1.070
0.041	42.17	25.95	30.50	1.628	1.175
0.030	59.35	35.67	44.45	1.662	1.245

Table IV. Determination of the equivalent neutral density of the 555 nm interference filter by comparing the recovery times for 700 μsec xenon flashes filtered through 0.9 and 1.2 neutral densities and the interference filter.

Letter B	Recovery times (sec)			Ratios	
(ml)	0.9 N.D.	1.2 N.D.	555 mμ	0.9 N.D. / 1.2 N.D.	555 mμ / 1.2 N.D.
2.69	5.47	3.93	5.12	1.391	1.302
0.49	7.94	6.67	7.78	1.190	1.165
0.14	11.13	9.51	10.33	1.170	1.089
0.066	14.02	12.27	13.47	1.143	1.098
0.041	21.17	17.07	19.20	1.240	1.125
0.030	30.55	25.65	27.70	1.190	1.080

increase in energy. It is interesting to note that the increase in recovery time for a twofold increase in flash energy for the tungsten light with a long-duration flash was almost twice as great as the same conditions for the short duration xenon flash. The ratio of recovery times for the 555 nm filter compared with the 1.2 neutral density was 1.143. This is an equivalent neutral density of 1.0 for the 555 nm interference filter for xenon light, in close agreement with the calculated values.

The results of the determination of the equivalent neutral density for the 555 nm filter for the two sources were used to equate the total luminous energy for 1.5 sec tungsten light flashes and 1.2 msec xenon flashes. The total integrated luminous energy in the flashes was 2.6×10^7 td·sec. The means of the recovery times for four subjects for the two types of flashes are shown in Table V. The last column of Table V is the ratio of the recovery times for the tungsten light flashes compared to the xenon flashes. The mean increase in recovery time for the 1.5 sec flash compared with the brief xenon flash was 35.8% The slightly reduced change in recovery time for the longer duration flash compared with the results of the first two experiments might be due to the influence of the different spectral distributions of the two flash sources.

Table V. Means of recovery times for four subjects for 20.4' Sloan-Snellen letters following 1.5 second tungsten light flashes and 1.2 millisecond xenon flashes. The total integrated energy in the flashes was 2.6×10^7 td·sec.

Letter B	Mean Recovery (sec)		
(ml)	1.5 sec tungsten	1.2 msec xenon	$\frac{1.5 \text{ sec}}{1.2 \text{ msec}}$
130.00	7.84	5.70	1.373
10.70	14.60	11.07	1.321
1.95	25.87	18.42	1.405
0.26	37.30	27.31	1.366
0.16	52.56	39.64	1.325

The results of the three experiments clearly indicate that long-duration flashes of the order of a second or more produce recovery times that are significantly longer than flashes in the millisecond range with the same integrated energy. This result is completely in accord with Hagin's findings on the bleaching of the photopigment in the rabbit eye. The mean increase in recovery time for the long-duration flashes of 42% compared with millisecond durations is equivalent to increasing the energy in the millisecond flashes by 3.5 times.

5. CONCLUSIONS

The results of Hagin's measurements of the photopigment bleached with short and long duration flashes correlate nicely with the increased recovery times found in this work for flash durations of a second or more compared with flashes in the millisecond range. Further work is indicated to check the course of the change in the recovery times with changing duration of flash. We have previously found a reciprocity failure for flashes between 500 μsec and 5 msec in duration. No data seem to exist comparing the recovery times for flash durations between the 5 msec range and those of the order of a second. The significant increase in recovery time for our long duration flashes of reduced rate of energy delivery is important in the area of flashblindness from nuclear detonations.

II. RECOVERY TIMES FOLLOWING BRIEF DOUBLE FLASHES WITH VARIOUS INTERVALS BETWEEN THE FLASHES

by

Norma D. Miller and Vincent M. King

1. INTRODUCTION

The effects of the temporal distribution of energy in high energy flashes on the afterimages produced were studied by Brindley.[15] He compared the afterimage produced in the lower half of a field by two intense flashes separated by 280 μsec or 4 msec with the afterimage produced in the upper half of the field by a single flash of approximately one half the total energy delivered to the lower portion. The flashes used had a duration of about 200 μsec. For a temporal separation of 280 μsec, the afterimages produced in the two portions of the retina were approximately the same brightness. The afterimages produced by two flashes with an interval of 4 msec between flashes were brighter than the afterimage produced by one flash. Previous work in this laboratory has shown that the recovery times to a fixed visual task are simply related to the instantaneous brightness of the afterimage following the flash. The present study was undertaken to investigate the effect on afterimage brightness of various

time intervals between two flashes of 250 μsec duration. The total integrated energy of the two flashes was approximately 1.5×10^7 td·sec. Recovery times for 20.4' Sloan-Snellen letters were used as the measure of afterimage brightness.

2. APPARATUS

The experimental apparatus was identical to that described in Part I. The only modification was the form of the sector disc placed adjacent to aperture A_2. Twelve discs were prepared, one for each of the 12 flash conditions. The duration of a single flash was controlled by the size of the notch cut out of a 10-inch cardboard disc. The interval between two flashes was controlled by the separation of the two notches. Sectors were made so that each flash was 250 μsec long at the half value of the resultant trapeziodal wave form. The interval between the two flashes, as measured from the half value point on the declining portion of the first flash to the half value point of the rising portion of the second flash, was varied in 100 μsec steps from 0 to 1000 μsec. The form of the disc and the resulting waveform of the flash are shown in Figure 3. The sectors were driven at 1780 rpm by a standard AC motor. The width of aperture A_2 controlled the rise time of each flash and the 2.5 mm width used produced a rise time of about 110 μsec.

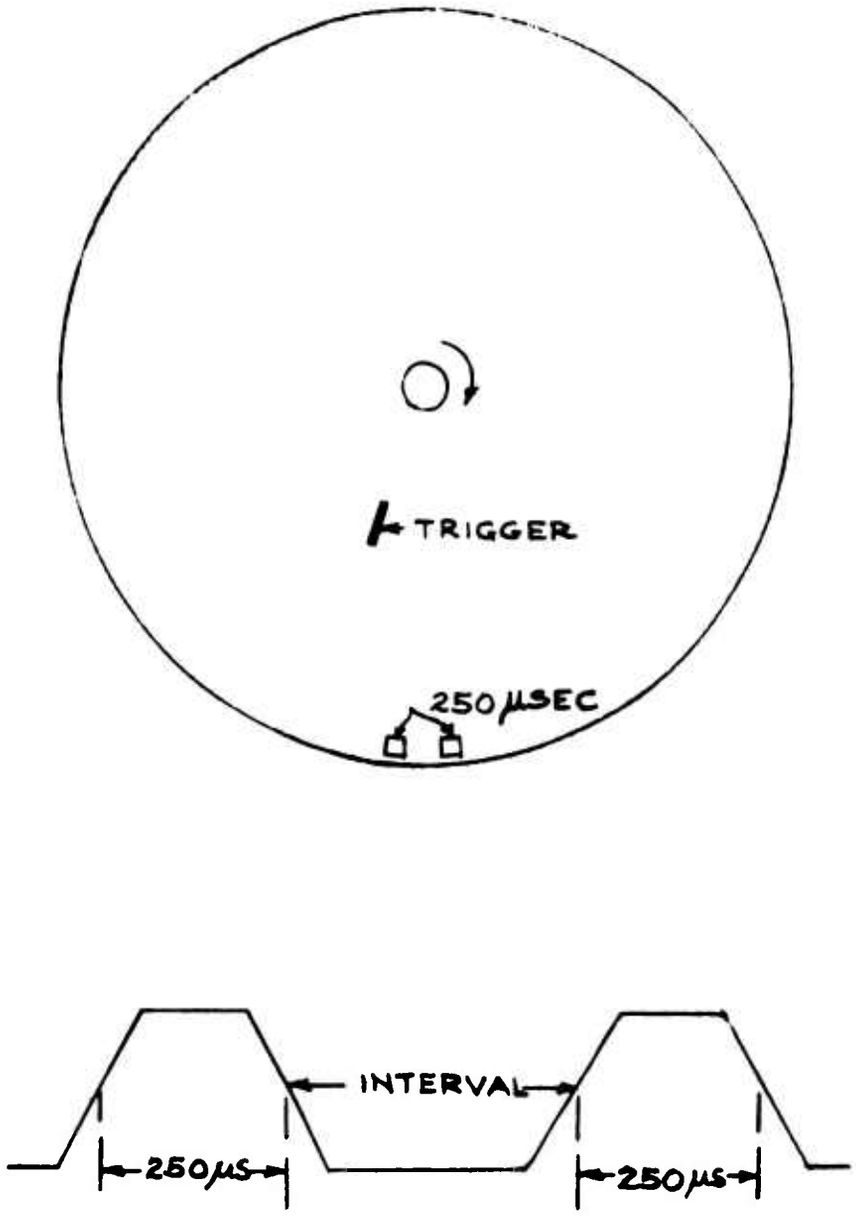

Figure 3. The form of the sector disc and the resulting double pulse of light. The interval in each case is measured from the half-height position.

The time course of the radiance of the xenon flash rises rapidly to a peak level, stays approximately constant for 1.5 msec, and then decays exponentially. In order to produce equivalent energies in each of the two flashes, the triggering of the flash tube had to be accurately controlled relative to the position of the sector discs. This was accomplished by cutting a slit in the sector disc near the center of the disc. A photodiode was placed in position behind the sector to receive light through the slit. A line image of the filament of a small lamp was focused by a cylindrical lens and acted as the source for the photodiode as the slit swept by. The photodiode was the trigger for the flash tube discharge, and it was activated at such a time as to insure that the peak luminance of the flash coincided with the opening in the sector. Minor adjustments in triggering time could be made by moving the trigger light or photodiode slightly. A rotary solenoid shutter covered the trigger slit until the subject was ready to receive a flash. The solenoid was then activated and the flash triggered within a revolution of the sector disc.

The duration of each flash of each sector and the time interval between the two flashes were calibrated by means of a Tektronix 555 oscilloscope. This calibration was repeated twice; once by using the time scale of the oscilloscope, and once

by using a time-mark generator so that fixed intervals of time were marked out on the photographs of the CRT. The duration of the second flash was measured by using the delayed trigger circuit of the oscilloscope for the second beam. This circuit delayed the electron beam of the second sweep across the cathode ray tube until the second flash fell on the phototube. This meant that the time of the beam sweep could be adjusted so the second flash filled the whole of the cathode ray tube face. The calibration of the energy in each flash and the total energy of both flashes was facilitated by integrating the current output of the phototube. Thus, the height of each trace gave an indication of the total energy in each flash. Each sector was adjusted by low-density filters or by carefully trimming the edge of the sector opening until the integrated energy for each was within a range of $\pm$ 5%.

3. EXPERIMENTAL PROCEDURE

Five male students in the School of Optometry of Ohio State University were used as subjects in this study. Prior to each experimental session, the subject was allowed to dark adapt for several minutes before the first of the xenon flashes was presented. There was a five-minute inter-trial period between flashes. While the afterimage is still perceived at

the end of a five-minute period, we have found that there are no cumulative effects after the first flash. The data for the first flash was recorded but not used in the analysis. The 11 flash intervals were presented to a subject in one experimental session which took about one hour. The various intervals were presented in random order, independently randomized for each subject. Thus, each interval was presented once during an experimental run, and each subject participated in only one experimental session per day. A total of five replications were done for each of the five subjects. A polaroid photograph of the CRT trace for each flash was made and read during the run so that, if the integrated flash energy deviated by more than $\pm$ 5% from the norm, that flash was repeated at the end of the sequence, and the data substituted.

In a second experiment the same experimental procedure was used but the flash energies were reduced by a factor of 2 by inserting a 0.3 neutral density filter in the flash beam. A third experiment in the series provided a base line for the change in recovery time as a function of change in flash energy. Nine flash conditions were presented in random order to each subject during one experimental session. Five replications were performed for each subject. The flash conditions were: a single

250 μsec flash through filters with neutral densities of 0, 0.3, 0.6, and 0.9; and a single 500 μsec flash through filters with neutral densities of 0, 0.3, 0.6, 0.9, and 1.2.

In all of the experiments the recovery times for six different luminance levels of Sloan-Snellen letters were recorded. The letters subtended 20.4 min of arc in their total dimension. The photographs of the CRT for each flash were recorded to provide a measure of the relative energy per flash.

4. EXPERIMENTAL RESULTS AND ANALYSIS

The experimental design in the first experiment of this series yielded 1650 individual recovery time determinations. In order to develop an analysis of the data that would result in an easy comparison of the effectiveness of the different flash conditions, various treatments were examined. Previous work in this laboratory has shown that there is a power relation between the target luminance and the recovery times for any flash condition. The data from the last experiment of the series for the 250 μsec flash filtered through two different neutral density filters is recorded in Table VI. The values in the table are the mean recovery times for the five separate replications for

Table VI. Subject means of recovery times in seconds for six target luminances following 250 usec flashes of different energy levels.

Subject	Target luminance (mL) 130.0	27.3	6.08	1.56	0.70	0.26
			2×10^7 td·sec flash			
R. E.	5.05	7.25	12.50	18.45	24.30	41.95
D. G.	5.60	9.50	11.40	13.80	23.30	50.95
J. M.	5.60	8.80	11.80	15.00	26.10	30.40
J. N.	4.50	7.25	9.70	13.15	16.15	30.85
W. P.	4.05	8.40	10.60	13.15	19.50	30.35
mean	4.05	8.40	11.20	14.71	21.87	36.90
			10^7 td·sec flash			
R. E.	3.90	6.00	9.05	12.65	17.35	28.60
D. G.	4.50	6.90	9.70	12.00	16.20	28.00
J. M.	5.00	7.00	8.60	12.65	16.30	29.90
J. N.	3.80	5.85	8.80	12.80	12.25	19.75
W. P.	3.70	6.60	9.85	13.05	15.55	27.95
mean	4.18	6.47	9.20	12.63	16.13	26.84
			5×10^6 td·sec flash			
R. E.	2.95	5.20	7.30	9.70	12.65	15.20
D. G.	3.40	6.70	9.00	11.30	14.30	16.60
J. M.	3.35	5.55	7.85	10.80	13.75	16.15
J. N.	2.95	5.10	7.55	9.90	12.20	16.95
W. P.	3.75	5.80	7.85	9.20	12.50	26.55
mean	3.28	5.67	7.91	10.18	13.08	18.29

each subject for each of the six luminance levels of the targets. The mean values for the five subjects are plotted in Figure 4 as the mean recovery time against the letter luminance for the three flash conditions. The graph shows the linear relation between the log of the letter luminance and the log of the recovery time. It also shows that the slope of this line remains constant with reduction in flash energy and is shifted parallel to the time axis for a given recovery time target luminance. Because of the linear relation between the log of the recovery time and the log of the luminance of the letter and the constant slope, the position of the line on the graph can be specified by the coordinates of a single point. This form of presentation of the data has the advantage that the mean increase in recovery times for various types of flash conditions can be more precisely determined by averaging over the log recovery times for a number of target luminances.

The data from the first experiment of the series are recorded in Table VII as the mean log recovery times for each subject for the six target luminances for each interval. The mean log recovery time for all subjects for each interval is recorded in the last column. The mean log vlaues for the five subjects in Table VII are shown graphically in Figure 5 as a function of the interval between flashes.

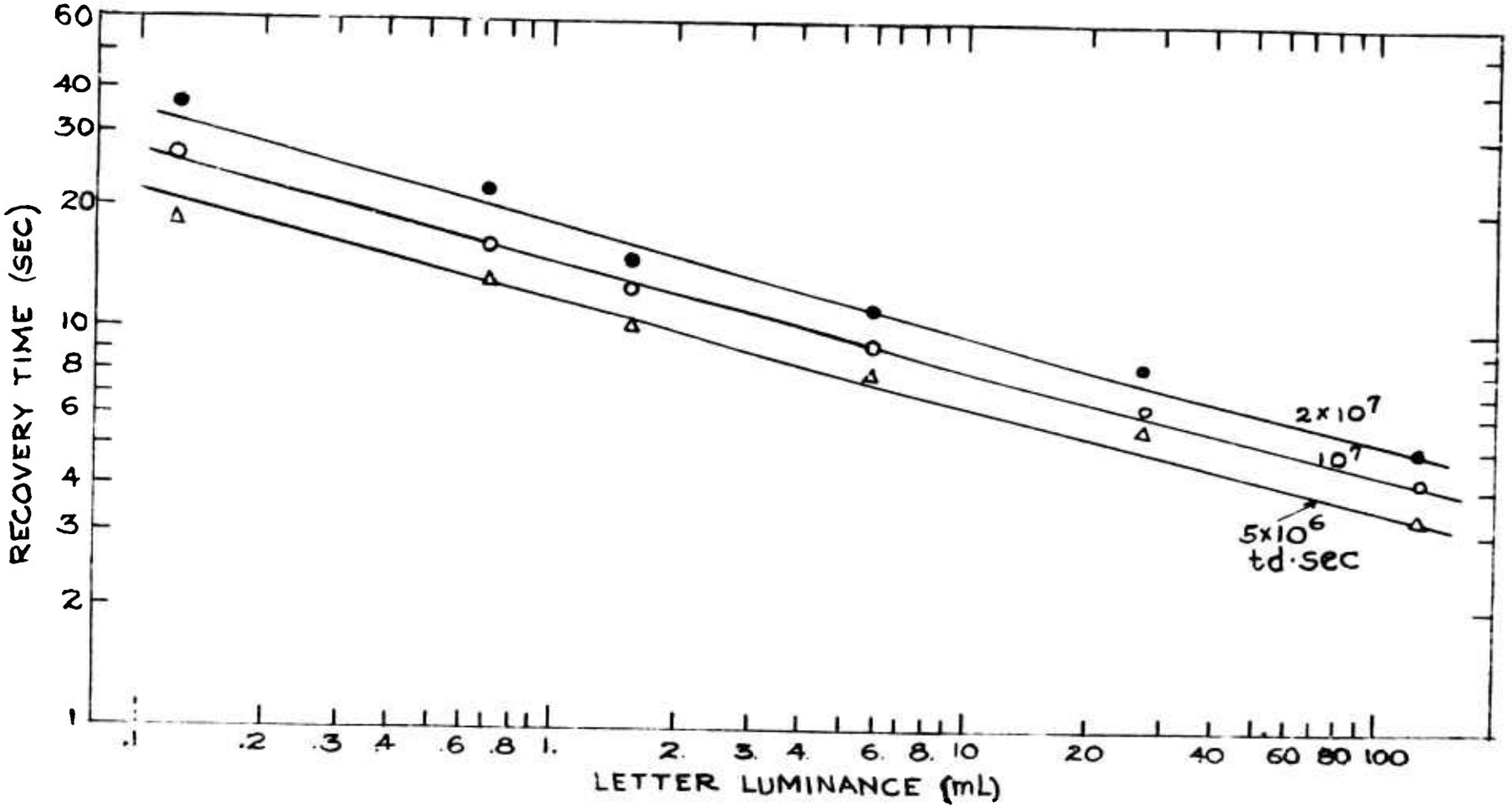

Figure 4. Form of recovery time curves for different luminance levels of the target letters and for different flash energies for 250 μsec flashes.

Table VII. Log mean recovery times for 20.4' Sloan-Snellen letters at six luminance levels following double flashes with various inter-flash intervals. The total integrated luminous energy for the two flashes was 2.5×10^7 td·sec.

Interval	Subject					
(μsec)	WP	JN	JM	RE	DG	mean
0	1.078	1.078	1.136	1.170	1.159	1.124
100	1.038	1.108	1.152	1.167	1.178	1.128
200	1.064	1.132	1.127	1,198	1.213	1.147
[illegible]	1.106	1.110	1.215	1.196	1.172	1.159
400	1.088	1.112	1.164	1.195	1.220	1.156
500	1.054	1.110	1.155	1.212	1.192	1.150
700	1.121	1.153	1.170	1.232	1.186	1.172
800	1.086	1.103	1.119	1.215	1.202	1.144
900	1.101	1.117	1.169	1.197	1.186	1.154
1000	1.115	1.107	1.170	1.221	1.181	1.158

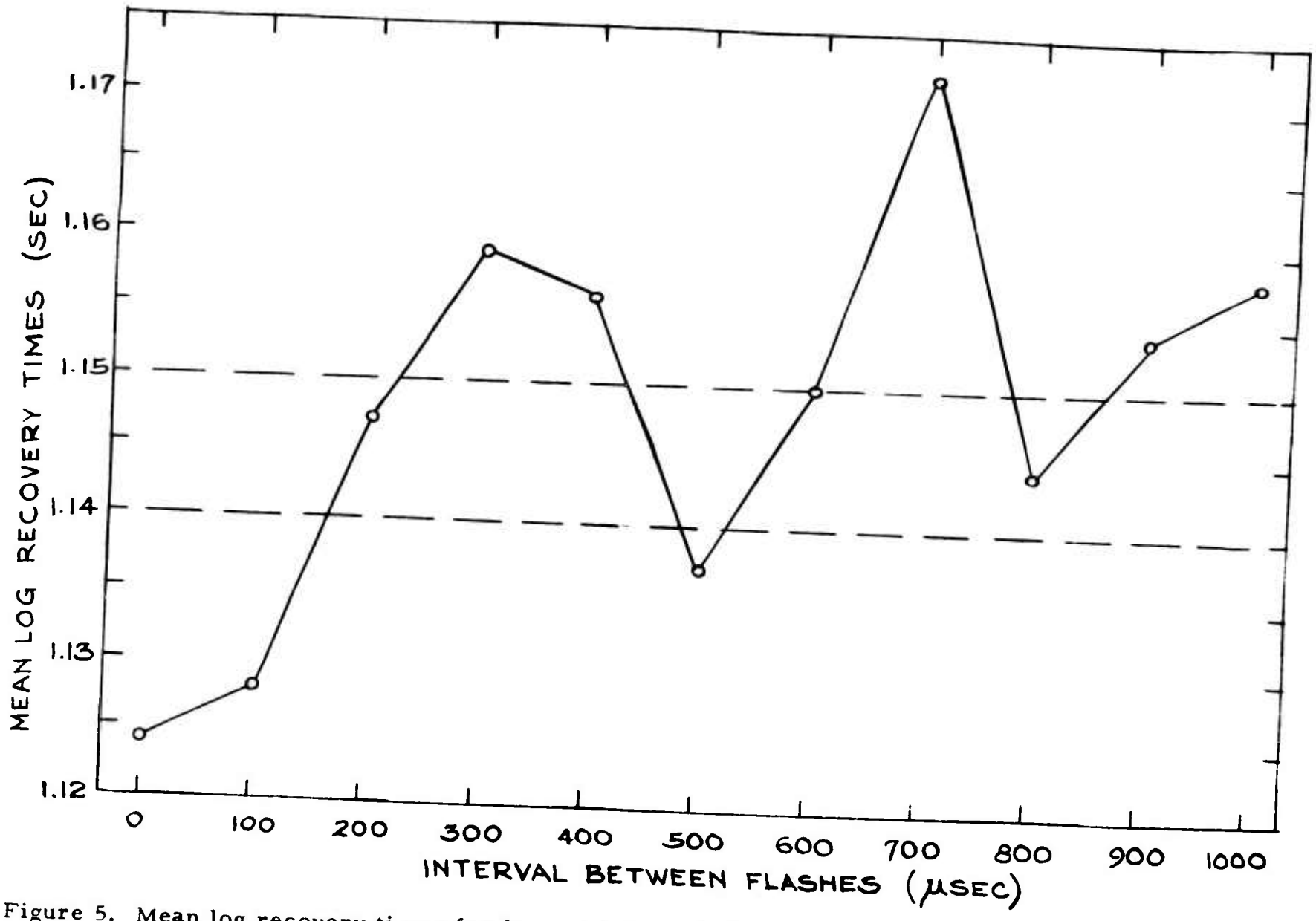

Figure 5. Mean log recovery times for five subjects and six target luminances following 2.5×10^7 td·sec luminous energy double flashes with various intervals between flashes.

The results of the second experiment with the flash energy reduced by one half are presented in Table VIII and in Figure 6 in the same manner as for the first experiment. There is a similar trend in the two curves of Figures 5 and 6. The curve for the 2.5×10^7 td·sec flash energy clearly depicts that increasing the intervals between the flashes from 0 to 300 μsec causes a continuing increase in the recovery time. Following this, there is a decrease in recovery time for intervals from 300 to 500 μsec. After reaching a minimum at 500 μsec, the recovery time increases again to a peak at 700 μsec. There are, of course, individual variations in these data.

The entire set of data for the 2.5×10^7 td·sec flashes was subjected to a rigorous statistical analysis by Dr. Harry Hughes of the Data Processing Section at the USAF School of Aerospace Medicine. The results of the analysis of variance are summarized in Table IX. The mean log of the five recovery replications were used as one item of raw data. The analysis was performed on one mean log recovery time for each of six luminances for each of eleven flash intervals for each of five subjects - a total of 330 numbers. The variation in the recovery time as a function of the interval between the two 250 μsec pulses is significant at the five per cent level (even close to the one per cent level).

Table VIII. Log mean recovery times for 20.4' Sloan-Snellen letters at six luminance levels following double flashes with various inter-flash intervals. The total integrated luminous energy for the two flashes was 1.2×10^7 td·sec.

Interval	Subject					
(μsec)	WP	JN	JM	RE	DG	mean
0	0.962	0.957	1.003	0.982	1.033	0.987
100	0.953	0.964	1.022	1.000	1.042	0.996
200	0.980	0.951	1.032	1.025	1.061	1.010
300	0.988	0.960	1.080	1.005	1.056	1.018
400	1.005	0.952	1.036	1.020	1.029	1.008
500	0.998	0.945	1.029	1.004	1.051	1.005
600	1.968	0.957	1.028	0.997	1.036	0.997
700	1.007	0.978	1.026	1.003	1.033	1.009
800	0.960	0.961	1.021	1.019	1.014	0.995
900	1.020	0.974	1.026	0.997	1.052	1.014
1000	0.971	0.933	0.999	1.030	1.084	1.003

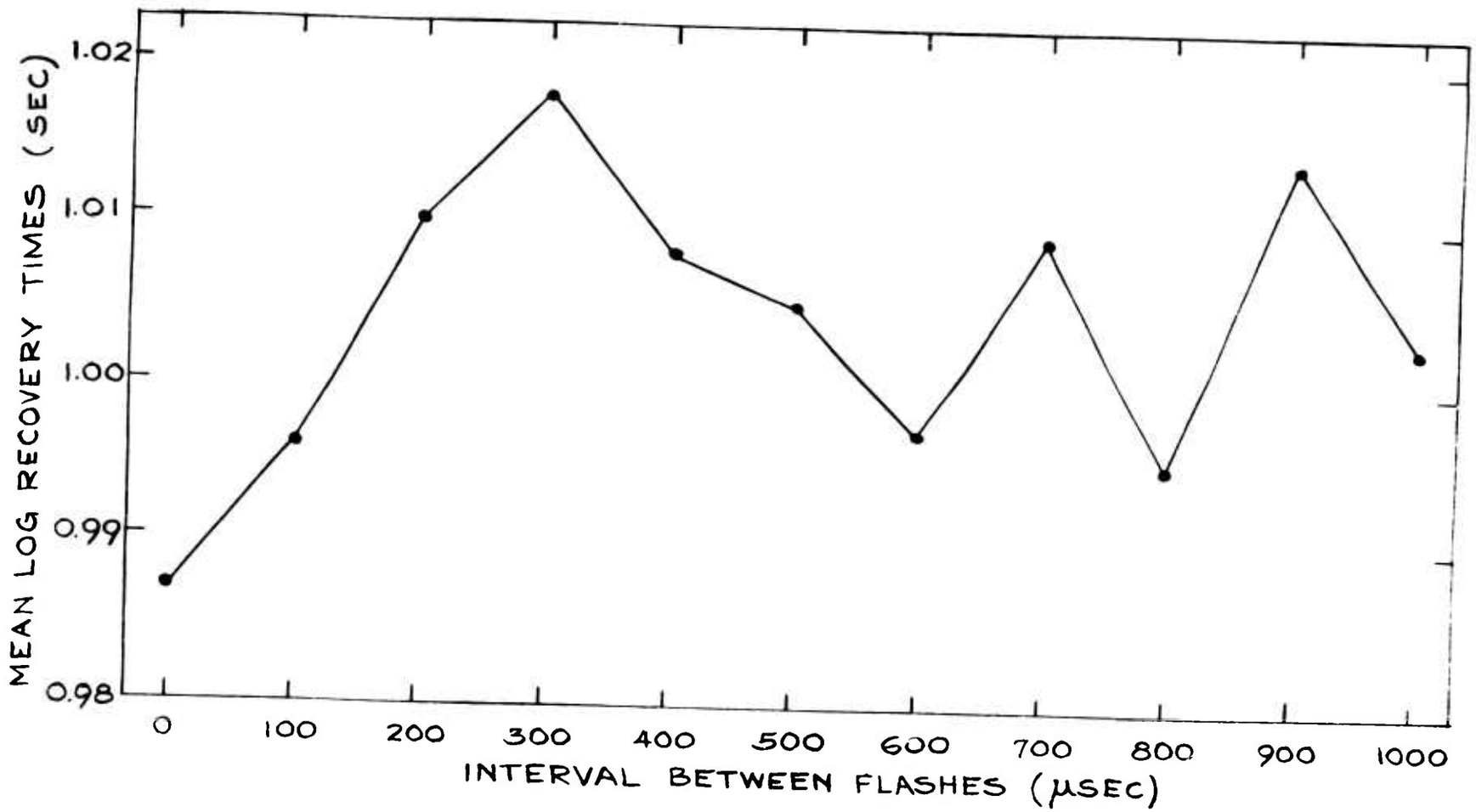

Figure 6. Mean log recovery times under conditions similar to those in Figure 5 except for a reduction in integrated flash energy to 1.2×10^7 td· sec.

Table IX. Analysis of variance table for double flashes of 2.5×10^7 td·sec.

Source	D. F.	S. SQ.	M. SQ.	F	P
Flash interval	10	.05973	.00597	2.59	<.025
Subjects	4	.61118	.15279		
F x S	40	.09225	.00231		
Luminance	5	25.29471	5.05894	542.17	<.001
L x S	20	.18662	.00933		
F x L	50	.05136	.00103	1.27	N. S.
F x L x S	200	.16185	.00081		

Duncan's range test was used to determine which flash intervals produced significantly different mean log recovery times. It was found that means lower than 1.140 may not be distinguishable and that means above 1.150 may not be distinguishable, but the two groups are significantly different from each other. This indicates that the recovery times for the 300, 400, and 700 μsec interval between flashes results in a significantly longer recovery time than that found for the 0, 100, or 500 μsec intervals.

In spite of the careful control of total integrated flash energy for all intervals, there was some small variation by interval. The mean flash energy for each flash interval was correlated with the mean recovery times. A coefficient of correlation between flash energy and recovery time of -.1136 was found. The value was nonsignificant. A two-way analysis of covariance on intervals by subjects was performed with energy as covariate. This treatment analyzes the effect of flash intervals after the effect of flash energy has been removed. The data for this purpose was the 55 values of mean log recovery from Table VII and the corresponding 55 values of mean relative energy per flash from Table X for each of the flash intervals for each of the five subjects. The resulting F ratio for flash intervals is

Table X. Mean relative energy in the 2.5×10^7 td·sec double flashes for the five replications of recovery time measurements for various intervals between flashes.

Interval	Subject					
(μsec)	WP	JN	JM	RE	DG	mean
0	2.81	2.80	2.80	2.72	2.75	2.781
100	2.83	2.82	2.81	2.75	2.77	2.800
200	2.82	2.79	2.85	2.78	2.72	2.803
300	2.87	2.81	2.81	2.73	2.80	2.811
400	2.78	2.83	2.79	2.75	2.70	2.781
500	2.73	2.73	2.77	2.69	2.71	2.735
600	2.79	2.77	2.82	2.73	2.74	2.781
700	2.85	2.79	2.78	2.70	2.73	2.723
800	2.80	2.70	2.73	2.70	2.68	2.723
900	2.71	2.64	2.69	2.59	2.65	2.670
1000	2.68	2.71	2.64	2.61	2.63	2.656

2.54, compared with 2.39 before removing the effect of energy variation.

The results become more meaningful if we compare the increase in recovery times caused by varying the flash interval with the changes in recovery time with flash energy. Reference to Figure 7 indicates the amount by which a 500 μsec flash would have to be increased in energy in order to provide the same mean recovery time as produced by two 250 μsec flashes separated by various intervals. The mean recovery times for all subjects and for the 130 mL target luminance for 500 μsec flashes of 10^7, 2×10^7 and 4×10^7 td·sec are plotted on Figure 7. The ordinates are the mean recovery times for each flash condition. The lower abscissae refer to the curves relating the recovery times to the intervals between the double flashes. The abscissae at the top of the graphs refer to the straight line connecting the data points for the three energy levels of 500 μsec flashes. The dotted lines indicate that the change in recovery for the 700 μsec interval compared with the zero interval is equivalent to more than a twofold increase in energy in a 500 μsec flash.

5. THEORETICAL INTERPRETATION

The general trend of the results from this experiment fit

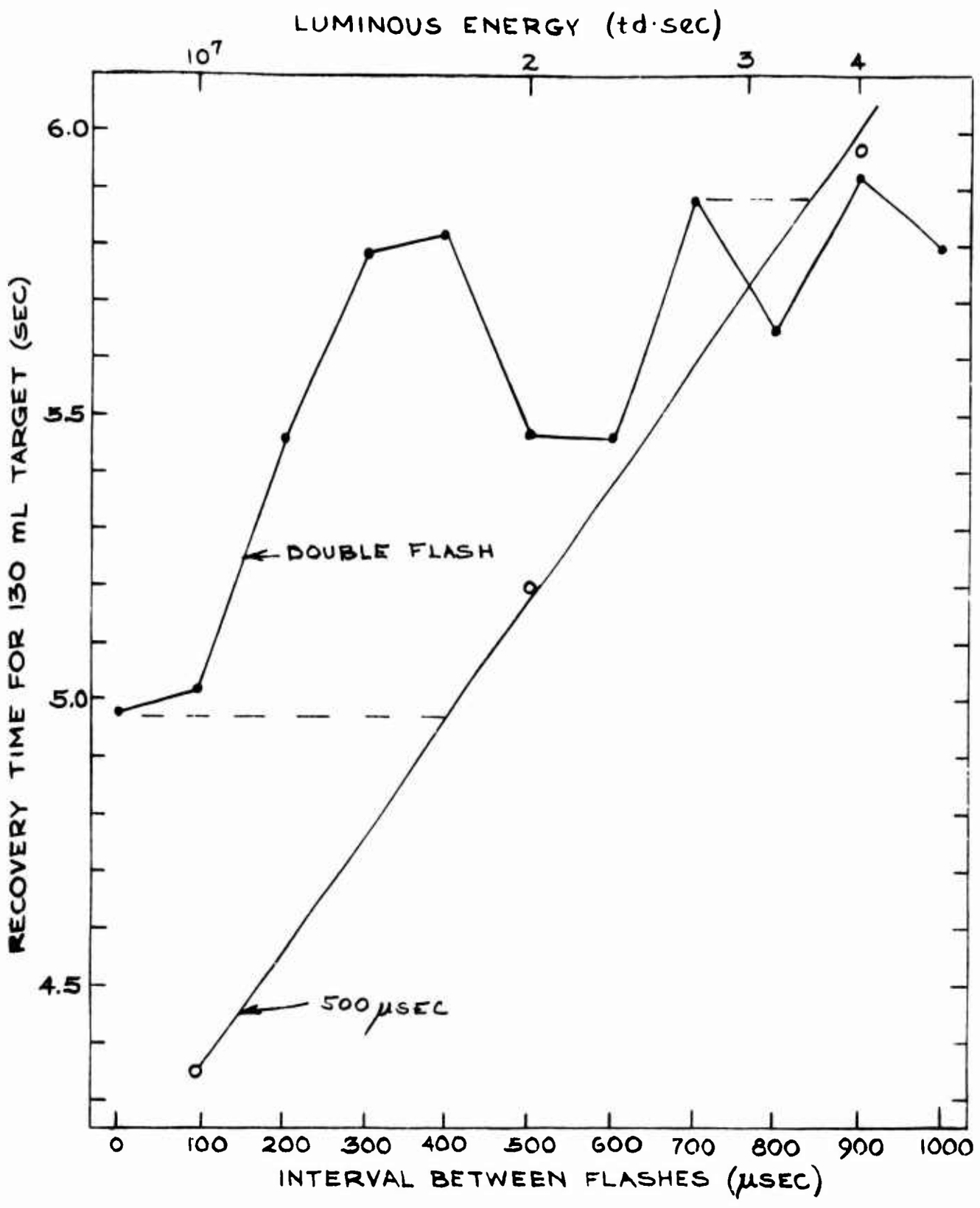

Figure 7. Mean recovery times for a 130 ml target luminance for 5 subjects following double flashes of 2.5×10^7 td·sec and following 500 μsec flashes of three energy levels.

nicely with the mathematical model developed by Williams, based on flash photolysis in rhodopsin solutions. The model implies that, if a molecule of visual pigment absorbs one quantum of light, it begins to thermally break down into a separate chromophore and protein components. During this process, it passes through several intermediate stages. Williams[12] proposed that, if another quantum is absorbed by this same molecule before the visual pigment hydrolyzed, the all-trans configuration of the chromophore is re-isomerized into a cis configuration. This means then, that if a particular molecule acts as though it had never absorbed the first quantum, a second one is absorbed within a msec. On the basis of this assumption the results of the 700 μsec interval of the present study could be explained. The pigments that had absorbed light from the first flash would hydrolyze before the second flash was delivered. Therefore, the second flash delivered 700 μsec after the first had little or no re-isomerizing effect on the pigment bleached by the first flash. The time course of events fits nicely with the experimental data of Hagin's on the bleaching of the pigment in the rabbit eye.

Williams observed that the photo-regenerated rhodopsin in solution had the same induced asymetry as natural rhodopsin. This suggests that the photo-regenerated rhodopsin is identical

to the natural pigment and should show the same characteristics as far as visual effects are concerned. That is, a short duration flash (less than 1 msec) is less effective in the production of bleached molecules than the same energy over a longer period of time. In the visual experiments just reported we can assume that we are dealing with the foveal photopigments and not rhodopsin. But, there is no reason to believe that the photo-reversal effect would not be the same in any type of visual pigments. As a matter of fact, Rushton and Baker[16] showed by objective densitometry that a 1 msec flash can only bleach about 60% of the foveal pigments no matter how intense the flash. Therefore, it does seem possible the re-isomerization effect occurs in the foveal cones as well as in the peripheral rods. A straight forward calculation of the number of quanta received by each retinal receptor from one of the two 250 μsec flashes indicated that the quantum density was high enough to produce a finite probability of one molecule capturing two quanta. There were approximately 6×10^8 quanta in each of the two pulses.

6. CONCLUSIONS

While the variation in recovery times are statistically significantly different for the different intervals between the flashes, the actual increase in recovery time is so small as to

be of no practical significance in an operational situation. The mean increase in recovery time for the six target luminances is of the order of 12% for the 700 μsec interval compared with the zero interval, or the 500 μsec flash. The mean increase in recovery time for the high-luminance target letters is 18%. The results are valuable, however, in that they are one more strong piece of evidence that the entire nature of the recovery time process is tightly tied to the chemistry of the photopigments. The fact that the psychophysical measures of the recovery time for these experiments fit the model derived on the basis of flash photolysis of rhodopsin solutions is clear indication that flashblindness results from events at the photochemical level of the retina.

III. VISUAL SENSITIVITY FOR VARIOUS WAVELENGTHS AS A FUNCTION OF ADAPTATION LEVEL

by

Norma D. Miller, Vincent M. King and John Schoessler

1. INTRODUCTION

Earlier work in this laboratory showed that the afterimage acts in the same manner as an external field of the same subjective brightness in raising the threshold for white light targets. Recovery times following an intense flash of light can be predicted on the basis of the measured instantaneous afterimage brightnesses. For both theoretical and practical reasons, it is important to determine whether or not the spectral sensitivity for any given afterimage brightness is the same as that produced by an equivalent white light field. Work by Sperling[17] and Hurvich and Jamison[18] has shown that the spectral sensitivity of the eye for narrow bands of wavelengths is a function of the adaptation of the retina. The most extensive investigations along this line have been conducted by Sperling, who has measured monochromatic increment thresholds for small test flashes superimposed on white light fields of various luminances.

The present work was undertaken as the first phase in an

effort to determine the wavelength sensitivity for various after-image conditions. Dr. Sperling generously permitted the use of his laboratory for this investigation. The two junior authors served as subjects to determine their spectral sensitivity curves for five different background luminance levels. They measured the increment thresholds for 45' test flashes of various wavelengths superimposed upon a 10^{o} white light field. The field luminances ranged from 5×10^{-5} td to 10 td for each subject.

2. APPARATUS

The apparatus is shown schematically in Figure 8. The tungsten ribbon filament lamp S serves as the source for both the surround and test fields. The surround channel consists of lenses L_1 and L_2, mirrors M_1 and M_2, the linear wedge WL, and field stop FS_1. Lens L_1 focused the ribbon filament source on wedge WL after reflection from the mirror M_1. The lens L_2 collimated the light passing through the wedge. The light was reflected into the field stop FS_1 by means of mirror M_2. The field stop was a variable aperture set to subtend 10^{o} at the eye of the observer. Lens L_3 focused the light from the field stop on the artificial pupil AP, a 2 mm-diameter aperture. This provided a Maxwellian view system.

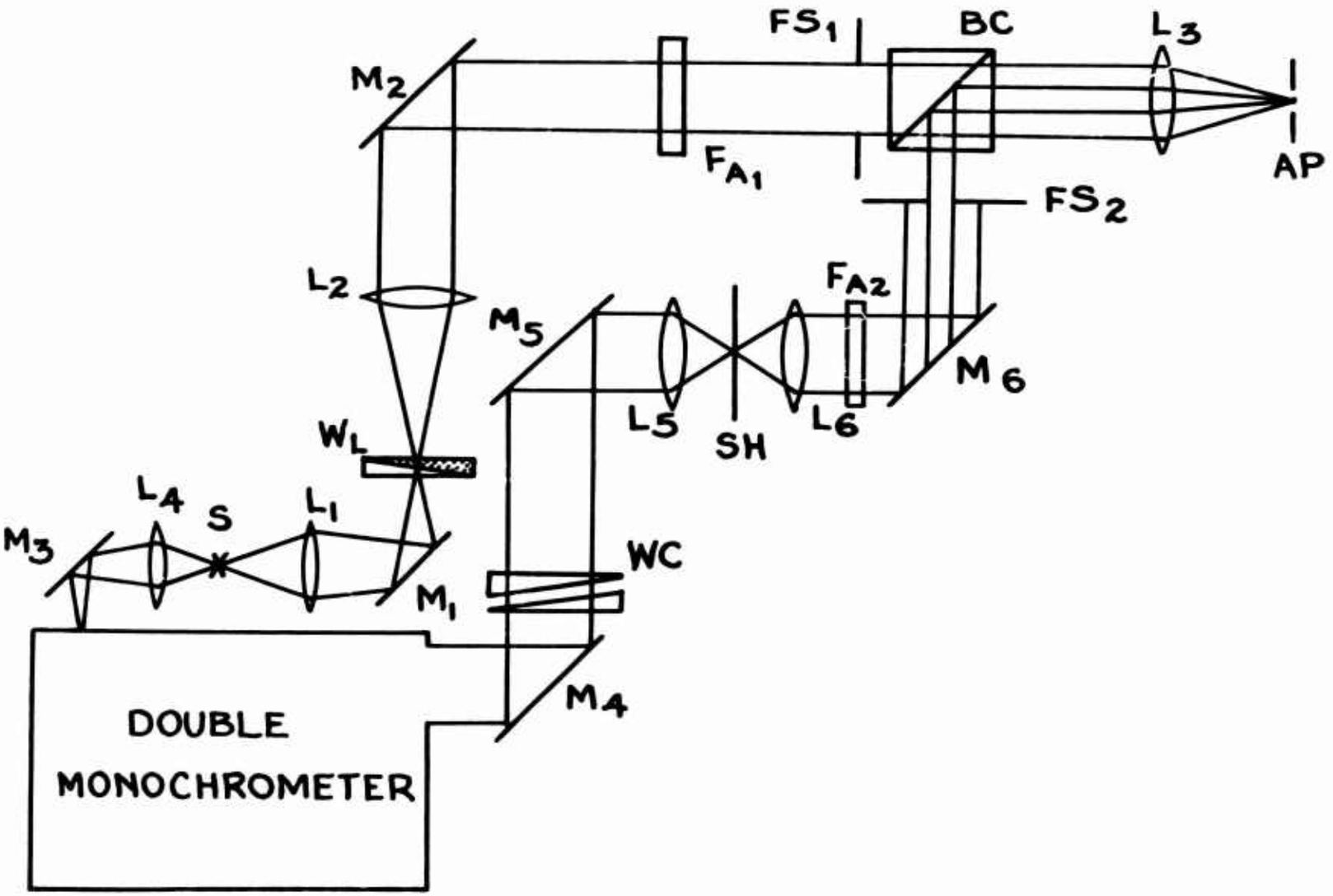

Figure 8. Schematic diagram of apparatus for determining the spectral sensitivity of the eye at various adapting levels. See text for explanation.

Auxiliary filters were placed at FA_1. These filters were a Wratten #78AA, which was used throughout the experiment; and additional neutral density filters which, in conjunction with the linear wedge, controlled the retinal illumination.

The test field was produced by the left channel of the system composed of the monochromator and lenses L_4, L_5, and L_6; mirrors M_3, M_4, M_5, and M_6; circular wedges WC; and field stop FS_2. The ribbon filament of the source was focused on the entrance slit of the Bausch and Lomb double monochrometer by means of lens L_4 and mirror M_3. The double monochrometer consisted of two diffraction grating monochrometers connected together so that the wavelength drum in one drove both gratings. The three slits of the monochrometer were set at 4 mm, (5mm at the 50,000 td level), to provide a half value spectral band width of 6.4 nm. The monochromatic light from the exit slit of the double monochrometer was reflected through the circular wedges WC by means of mirror M_4. Mirror M_5 and lens L_5 reflected and focused the light in the plane of the shutter Sh. Lens L_6 then collimated the beam; and, after reflection from mirror M_6, the light passed through the field stop FS_2. The field stop aperture subtended 45' at the eye of the observer. The field stop was seen in the center of the background field by

means of the beam combiner BC. The monochromatic test field was also presented in Maxwellian view by means of lens L_3. Supplementary neutral density filters were placed at FA_2. These filters were of such density that the whole range of test light intensity required for a given level of retinal illumination could be provided by adjustment of the circular wedge WC.

The subject positioned his right eye behind the artificial pupil AP for the experimental runs. This position was maintained by means of a fixed support for a wax dental impression biteboard.

3. CALIBRATION

Throughout the experimental sessions the ribbon filament lamp was operated at 16.6 amps except for the highest background luminance condition which required raising the current to 17.5 amps. The spectral irradiance from the double monochrometer was measured with an EG & G Spectroradiometer and with a calibrated EG & G photodiode. The results were compared with previous measurements made in Dr. Sperling's laboratory with a thermopile. The spectral transmittance of all neutral density filters used in the test flash beam was also measured with the Spectroradiometer. The relative spectral irradiance for

each wavelength band for the various filter combinations used for the different background luminances are listed in Table XI. The values listed represent the maximum irradiance available for each condition.

The threshold determination was made by adjusting the density wedges to attenuate the light from the monochromators. The wedges were calibrated by means of the Spectroradiometer and found to be linear over the range used; but, due to selective absorption, the slopes of the calibration graphs were different for various wavelength regions. The change in density per unit change in wedge setting is shown in Figure 9 as a function of wavelength.

The background field beam was adjusted by means of a double linear wedge of Chance neutral density glass and by the insertion of neutral gelatin filters. A MacBeth illuminometer was used to determine the various background conditions. The MacBeth test plate was placed 30 cm behind the artificial pupil and the linear wedges were set to produce the required illumination on the test plate. The retinal illumination in trolands can be calculated directly from the MacBeth reading by:

$$\text{Ret. ill. (td)} = d^2 \times 10^6 \times E$$

Table XI. Log spectral irradiance at the eye from double monochromator for each background condition. (Arbitrary units)

λ(nm)	10 td	10^2 td	10^3td	10^4td	5 x 10^4 td
400	1.922	2.934	4.268	4.866	5.209
10	2.200	3.180	4.477	5.063	5.403
20	2.411	3.372	4.626	5.181	5.549
30	2.658	3.577	4.797	5.339	5.680
40	2.823	3.719	4.908	5.433	5.778
50	2.990	3.791	4.954	5.532	5.867
60	3.114	3.966	5.106	5.612	5.952
70	3.230	4.069	5.191	5.685	6.012
80	3.307	4.137	5.239	5.720	6.056
90	3.369	4.183	5.285	5.757	6.087
500	3.402	4.204	5.318	5.796	6.129
10	3.453	4.237	5.352	5.826	6.159
20	3.470	4.266	5.378	5.849	6.199
30	3.505	4.287	5.395	5.857	6.201
40	3.545	4.332	5.432	5.898	6.236
50	3.596	4.373	5.468	5.931	6.262
60	3.607	4.389	5.489	5.953	6.276
70	3.602	4.379	5.493	5.958	6.282
80	3.612	4.389	5.492	5.960	6.279

Table XI. (continued)

λ(nm)	10 td	10^2td	10^3td	10^4td	5 x 10^4 td
90	3.643	4.398	5.475	5.931	6.250
600	3.602	4.370	5.417	5.881	6.191
10	3.596	4.364	5.416	5.889	6.182
20	3.597	4.378	5.443	5.919	6.219
30	3.592	4.382	5.468	5.957	6.255
40	3.553	4.357	5.463	5.958	6.255
50	3.555	4.367	5.479	5.972	6.270
60	3.552	4.364	5.473	5.969	6.266
70	3.544	4.355	5.456	5.942	6.234
80	3.526	4.292	5.430	5.926	6.232
90	3.449	4.283	5.390	5.896	6.219
700	3.380	4.229	5.326	5.809	6.139

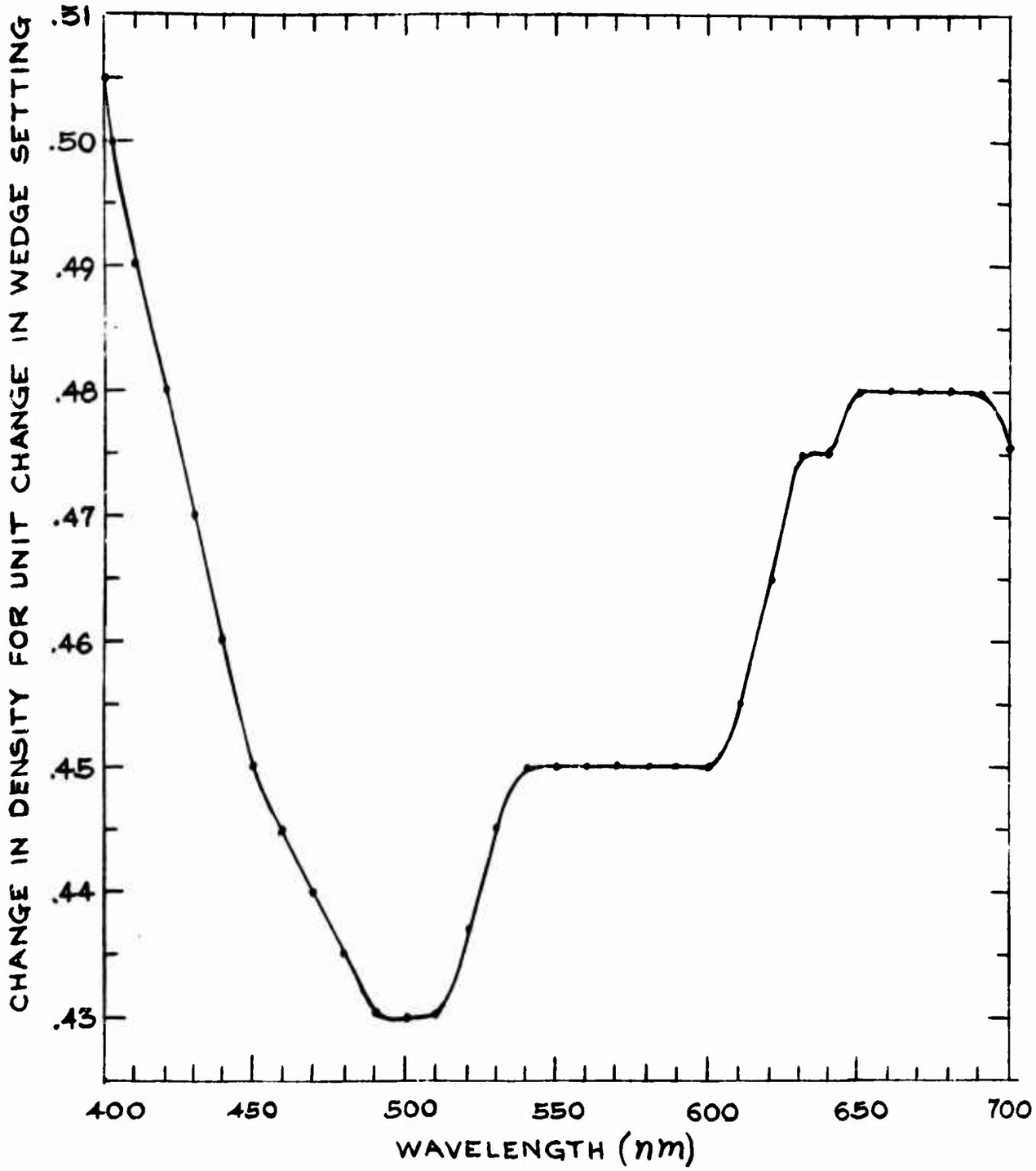

Figure 9. Calibration curve for density wedges in the monochromatic test beam.

where d is the distance in feet from the test plate to the artificial pupil, and E is the illumination on the test plate in foot-candles.

A Wratten 78AA filter was used in the background beam at all times and a Wratten #96 neutral density filter of 3.1 density was used for the 10 td background. An infrared blocking filter was used for the 50,000 td background. The spectral absorption of the linear wedges was not measured, so the exact spectral distribution of the background for all conditions cannot be precisely stated. There was some change in the distribution due to the addition of the 3.1 neutral density and due to the change from 16.6 amps to 17.5 amps for the operating current for the 50,000 td case. The curves in Figure 10 show the approximate form of the distribution curve for the 10 and 10,000 td conditions.

4. EXPERIMENTAL PROCEDURE

The two male subjects were in their middle twenties. Both had normal color vision and were given complete clinical eye examinations. Both subjects wore corrective spectacle lenses throughout the experimental work.

Thirty-one narrow wavelength regions between 400 nm and

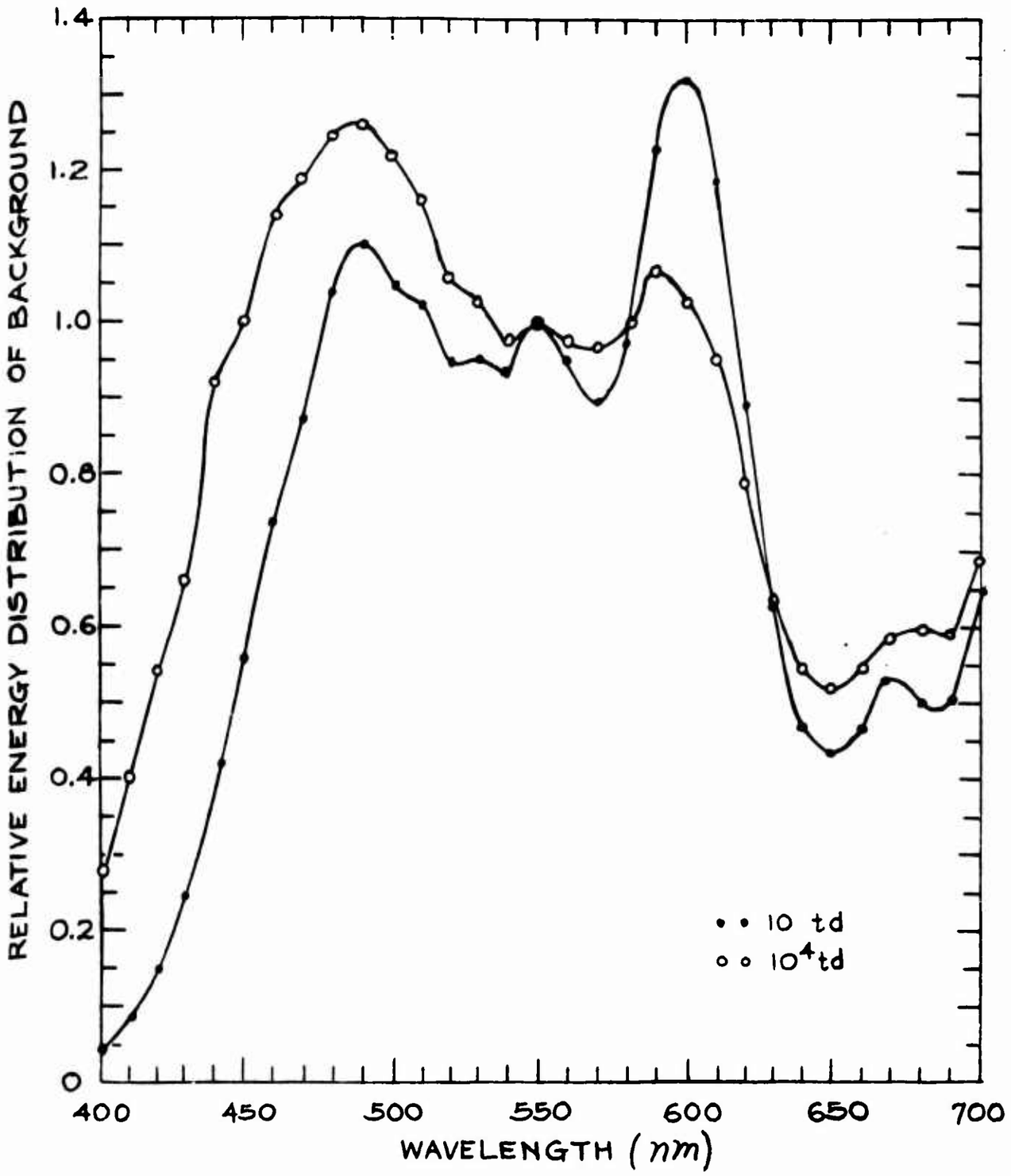

Figure 10. Relative energy distribution of the white light background field at two retinal illuminance levels.

700 nm were tested in the threshold measurements. Each subject participated in two experimental sessions per day; one in the morning and one in the afternoon. During each experimental session, two separate thresholds were determined for each of the wavelength regions. At the beginning of each session the test flash was presented well below threshold and the intensity increased on successive presentations until the subject signaled that it had been perceived against the white background field. The 31 wavelength bands were presented in random order, independently randomized for each session. During the second half of the experimental session, after a five-minute break, the thresholds were redetermined starting from above the threshold condition and lowering the intensity at each presentation until the flash was no longer seen. The last perceived intensity was recorded as the threshold. There were ten replications of the sessions for each subject and for each background luminance condition except for the 5×10^4 td background where only six replications per subject were performed.

The experimenter set the wavelength drum to select the wavelength band indicated by the random order chart. The 390 msec flashes were presented at the rate of about one per second. Following each presentation, the density wedges attenuating the light from the monochromator were changed by 0.05 in density,

either increasing or decreasing depending upon the type of threshold determination being made. The data were in terms of the density wedge setting for threshold for each wavelength for each background condition.

5. EXPERIMENTAL RESULTS

The wedge density values for each threshold determination were calculated from the calibration data for the wedges. The density values were subtracted from the appropriate log irradiance values of Table XI. The antilogs of the 40 threshold determinations were averaged to give a mean relative threshold energy for each wavelength band and each background condition. The results of the data reduction are listed in Table XII. The data are shown graphically in Figure 11 for the five background conditions. The ordinates are relative energy values, but the care exercised in the calibration insures that the various curves are in the true relative position. Inspection of Figure 11 reveals some interesting changes in the amounts of energy required for the increment threshold as the background level is increased. The lowest curve (10 td background) shows a slight increase in threshold at 580 nm and 590 nm compared with the wavelengths on either side. The 10^4 td background curve, however, shows a

Table XII. Mean relative energy for 45' monochromatic increment threshold flashes superimposed on a 10^{o} white light adapting field of various luminance levels.

Test flash λ (nm)	Adapting field level (td)				
	10	100	1000	10,000	50,000
400	12.12	190.18	2731.0	16323	31893
410	15.14	141.99	1106.0	8248	27828
420	9.68	105.30	710.0	4999	20290
430	12.89	103.70	786.5	5784	22366
440	11.43	87.73	750.3	5314	51081
450	13.20	85.29	705.7	6733	36457
460	11.65	98.20	948.4	7767	58153
470	12.50	95.74	860.8	8253	44914
480	9.25	92.48	917.1	8129	39527
490	6.81	72.99	946.3	8216	30539
500	2.88	42.06	569.6	5461	18317
510	2.37	31.24	438.4	4148	16314
520	2.11	19.83	276.4	2936	10987
530	2.32	18.93	256.9	2900	10005
540	1.63	16.90	255.7	3034	15274
550	2.32	19.16	269.2	4012	16364

Table XII. (continued)

Test flash λ(nm)	Adapting field level (td) 10	100	1000	10,000	50,000
560	1.94	29.66	346.1	4535	34190
570	2.51	25.77	530.1	5916	19245
580	3.02	28.69	45[illegible].5	5234	25953
590	3.04	28.26	388.8	3355	11128
600	2.37	24.15	251.6	2325	17220
610	2.57	19.43	256.1	2223	13098
620	2.47	30.19	251.9	2434	13061
630	3.44	41.91	411.2	3613	22944
640	5.68	58.73	488.1	4884	38903
650	11.62	90.19	1390.0	8816	45924
660	25.56	156.37	1558.0	15916	87838
670	34.57	365.81	2971.0	30509	120713
680	79.92	741.40	5779.0	64414	187628
690	156.10	2773.00	17162.0	154087	240456
700	307.10	2920.00	31634.0	177249	280283

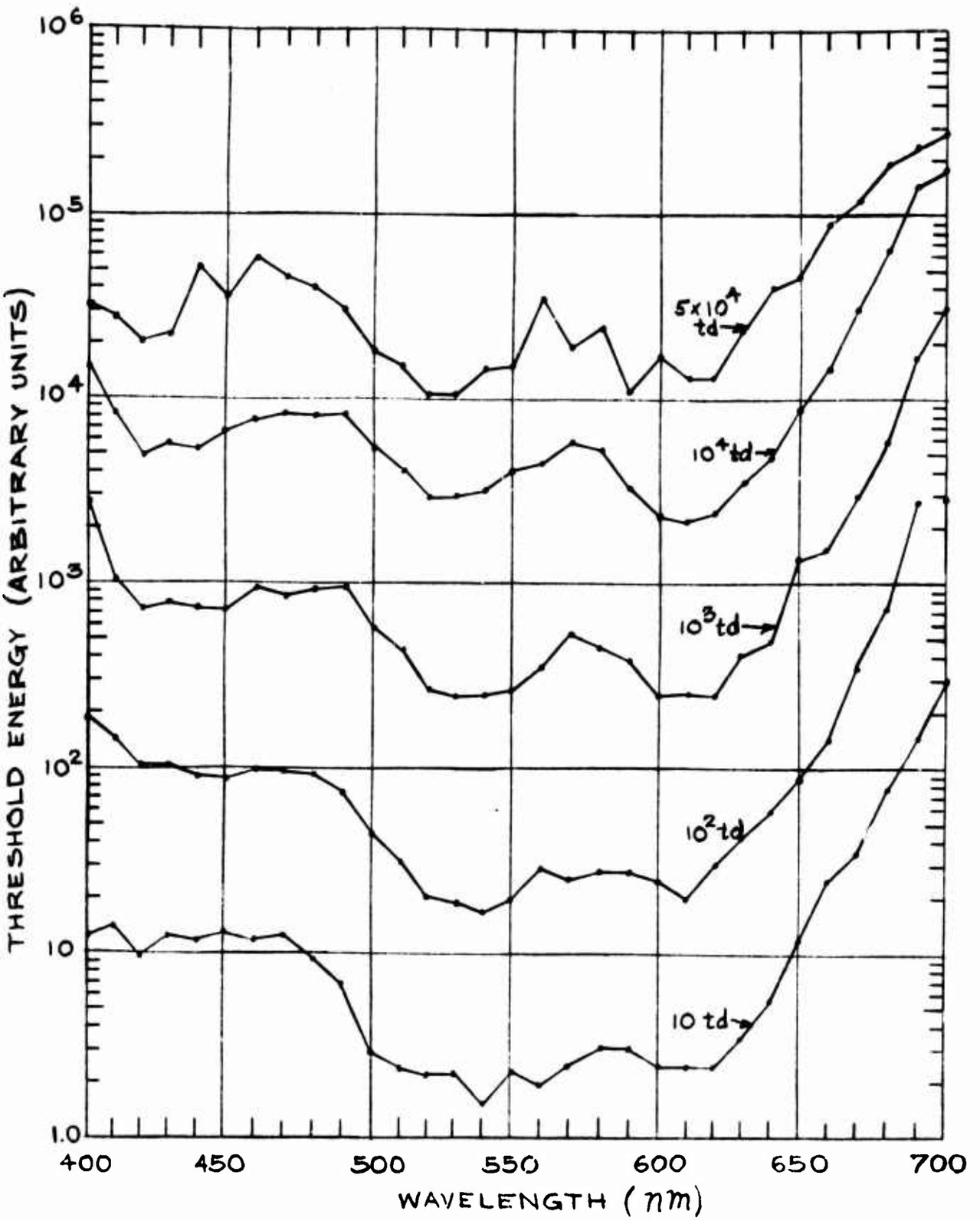

Figure 11. Thresholds for 45' monochromatic test flashes superimposed on a 10^{o} white light background of various illuminance levels.

marked increase in threshold peaking at 570 nm compared with 540 and 600 nm. The graphs in Figure 12 show the selective changes for various wavelength bands even more clearly. The slope of the lines connecting the data points for 480, 530 and 600 nm is approximately one while the slope for 430 is considerably less and for 560 nm considerably greater than one. The threshold energy for 430 nm must be increased by a factor of 7.2 for each decade increase in background luminance. The threshold at 560 nm, however, requires a 14.5 times increase for each decade increase in background.

The mean relative thresholds are shown replotted in Figure 13 for the 10^2, 10^3 and 10^4 td backgrounds. The curves are the same as in Figure 11 with the exception that the 10^3 and 10^4 td curves have been lowered along the Y axis by one and two decades. One interesting feature of Figure 13 is the fact that the three curves are almost exactly superimposed on the long wavelength side. Another interesting feature shown by the 10^4 td background curve is the fact that more energy is required at 570 nm than is required at 420 nm for detection of the test flash. Even though Figure 10 shows that there is some change in the background energy distribution, the amount of change does not seem adequate to explain the relative changes in sensitivity at 610 nm and 530 nm.

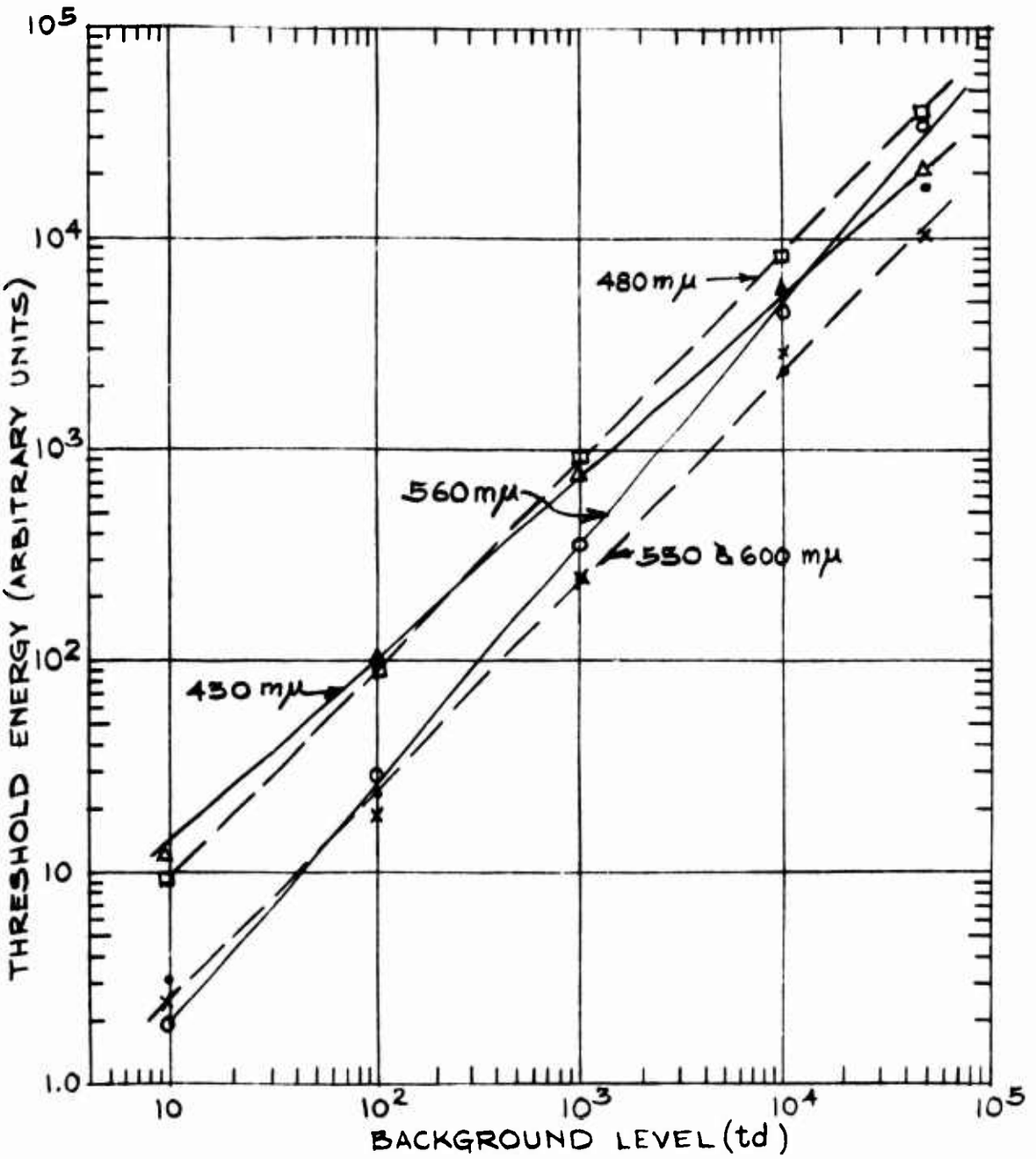

Figure 12. Increase in monochromatic threshold energy with increase in white light background illuminance for several wavelengths.

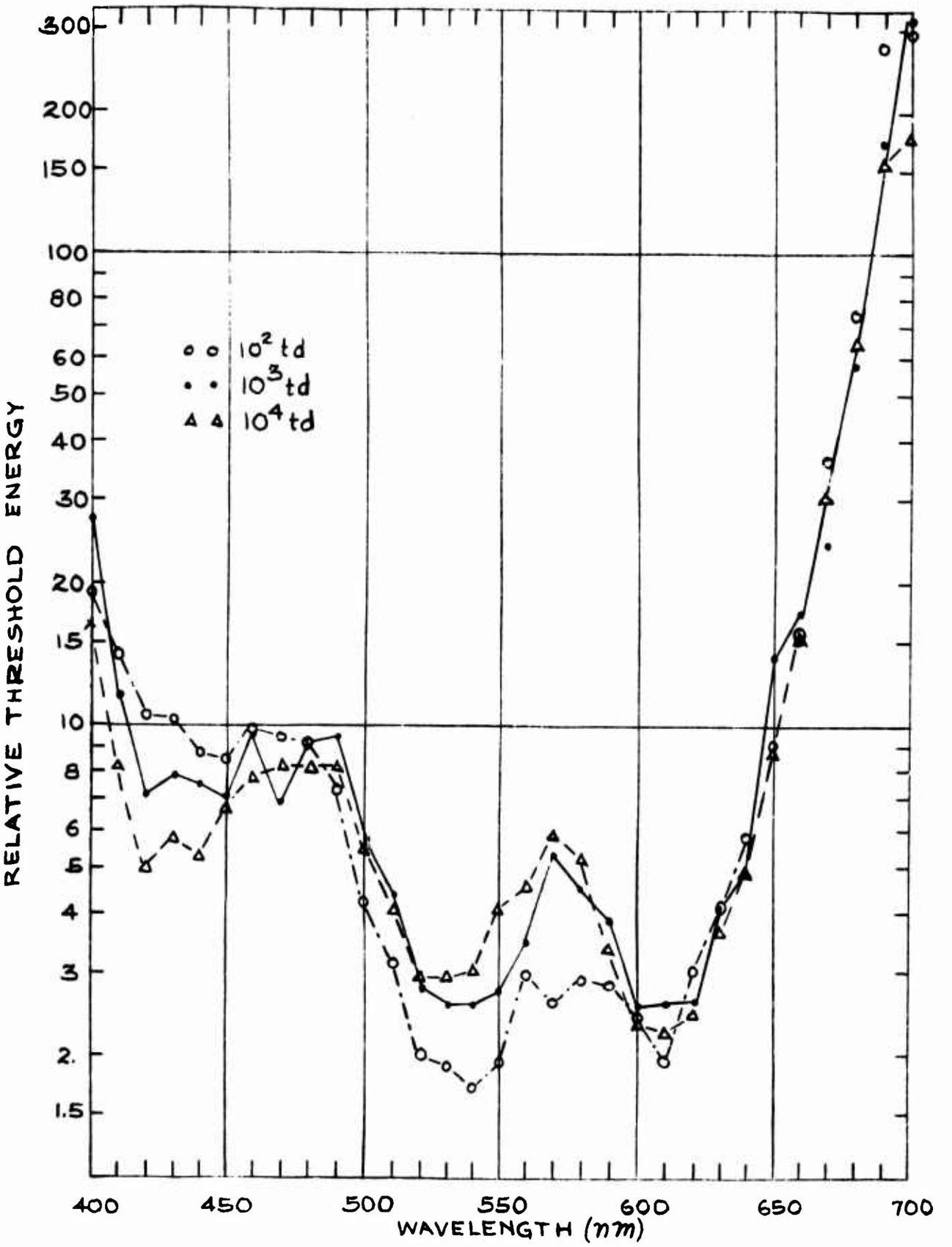

Figure 13. Relative energy in monochromatic threshold flashes superimposed on various white light background illuminances showing the change in spectral sensitivity with adaptation level.

The inverse of the threshold energy for the 100 td background is shown plotted in Figure 14 compared with the luminous efficiency curve as defined by the 1931 Standard Observer. The inverse of the threshold energy required for absolute threshold as determined by Dillon and Zegers[19] is also plotted in Figure 14. The luminous efficiency curve of the 1931 Standard Observer has frequently been criticized as being too low in blue sensitivity. The absolute threshold values as determined by Dillon and Zegers show clearly the increase in blue sensitivity for their experimental determination. Even so, the results from the increment threshold determinations superimposed on a 100 td background are not similar to either of the luminous efficiency curves. If the three curves are brought into coincidence on the long-wavelength end, the 100 td background condition shows a marked dip in sensitivity through the green region as well as a heightened sensitivity in the blue even as compared with the Dillon and Zegers measurements.

6. COMPARISON OF RESULTS WITH PREVIOUS WORK

It is probably not surprising that the increment threshold determinations produce a different function for visual sensitivity than the conditions used in determining the basic luminous

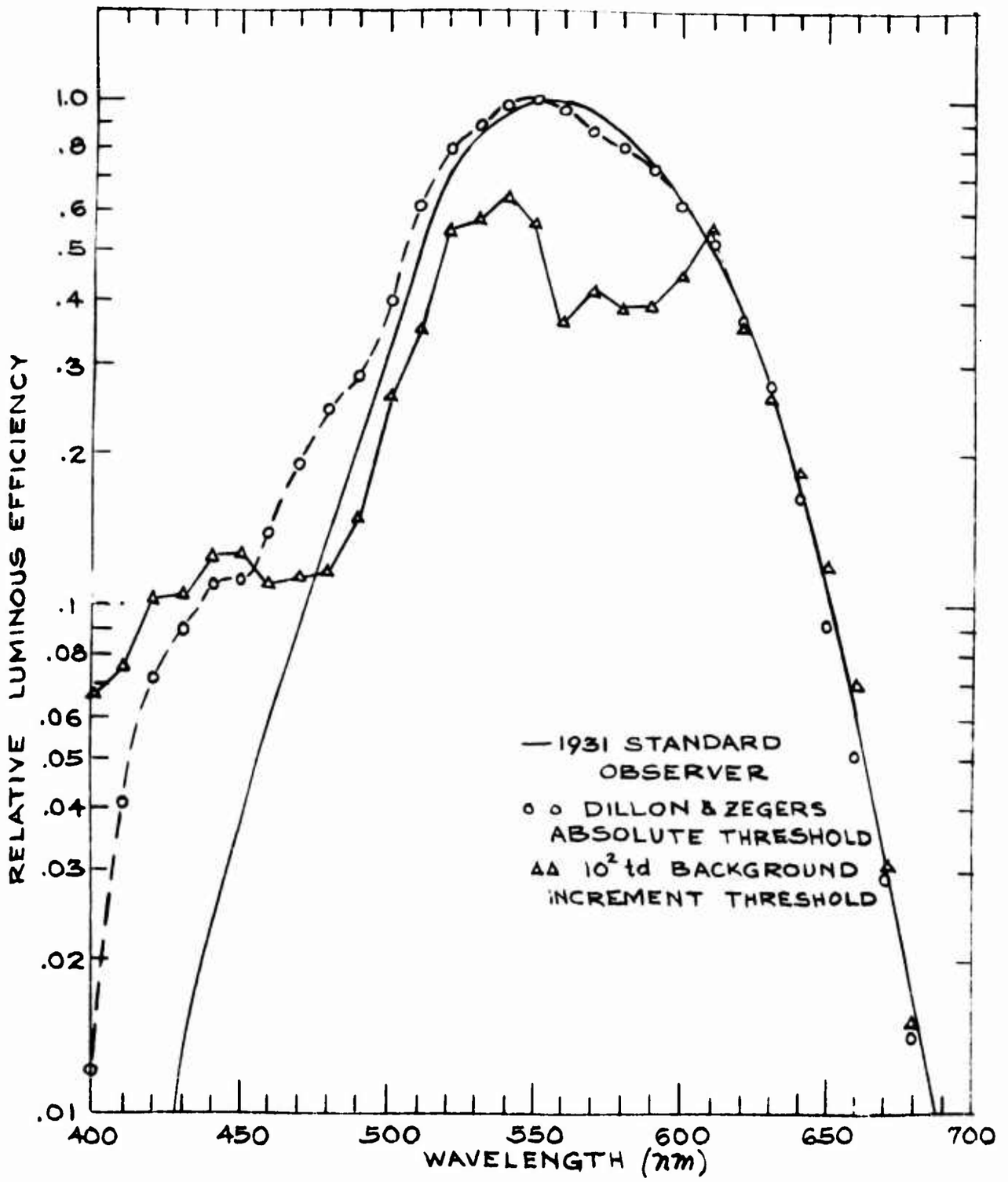

Figure 14. Comparison of the relative luminous efficiency of monochromatic light as defined by the 1931 Standard Observer and measured for absolute threshold flashes by Dillon & Zegers and for 45' test flashes superimposed on a 10^2 td white background.

efficiency curves. In the present investigation where a small test flash was superimposed upon a continuously exposed white light field, the criterion for detection is different from the condition of heterchromatic matching of stimuli used in the step-by-step method of determining the luminous efficiency curve. It is also not surprising that the increment threshold technique produces a different type of sensitivity than that found by the absolute threshold method. It is a well-established fact that local adaptation of a selective chromatic nature produces a change in the spectral sensitivity.

The conditions used in this study were such as to measure the least perceptible change in saturation of the test stimulus. In this respect they are more nearly similar to the conditions used by Priest and Brickwedde[20] in their determination of the minimum perceptible colorimetric purity. Inasmuch as the test flash is superimposed on the white light field, the stimulus to be detected is a mixture of the white light and the monochromatic stimulus, and the subject's task is to discriminate either on the basis of luminosity change or on the basis of a detectable chromoticity change. In Priest and Brickwedde's experiments a 4^{o} bipartite field was used with a retinal illuminance between 70 and 90 td. The energy distribution of the 4^{o} field was that of

Abbot-Priest sunlight. As the spectrally pure component was added to the right half of the bipartite field, the luminance was maintained at a constant level by subtracting some white light from that side. They defined colorimetric purity as $\Delta B_s/(\Delta B_s + B_{white})$. The luminance of the monochromatic stimulus ΔB_s was measured by means of flicker photometry. The colorimetric purity determined by Priest is shown plotted in Figure 15. The increment thresholds found in our investigation for the 10^4 td background field have been converted to luminance units by multiplying by the luminous efficiency values of the 1931 Standard Observer and are plotted on the same graph. There is a strong similarity between the two functions even though the methods of determination were different. There is considerably less agreement with the threshold purity curve for the lower background luminance levels, probably indicating that the change in luminosity of the monochromatic stimulus was also used in detecting the target flash.

In 1942 MacAdam[21] published the results of an extensive investigation to find the visual sensitivities and color differences in daylight. He used a 2^o bipartite field within a surrounding field subtending 42^o. The surround field was maintained at a chromaticity similar to that of the ICI Standard C Illuminant. The

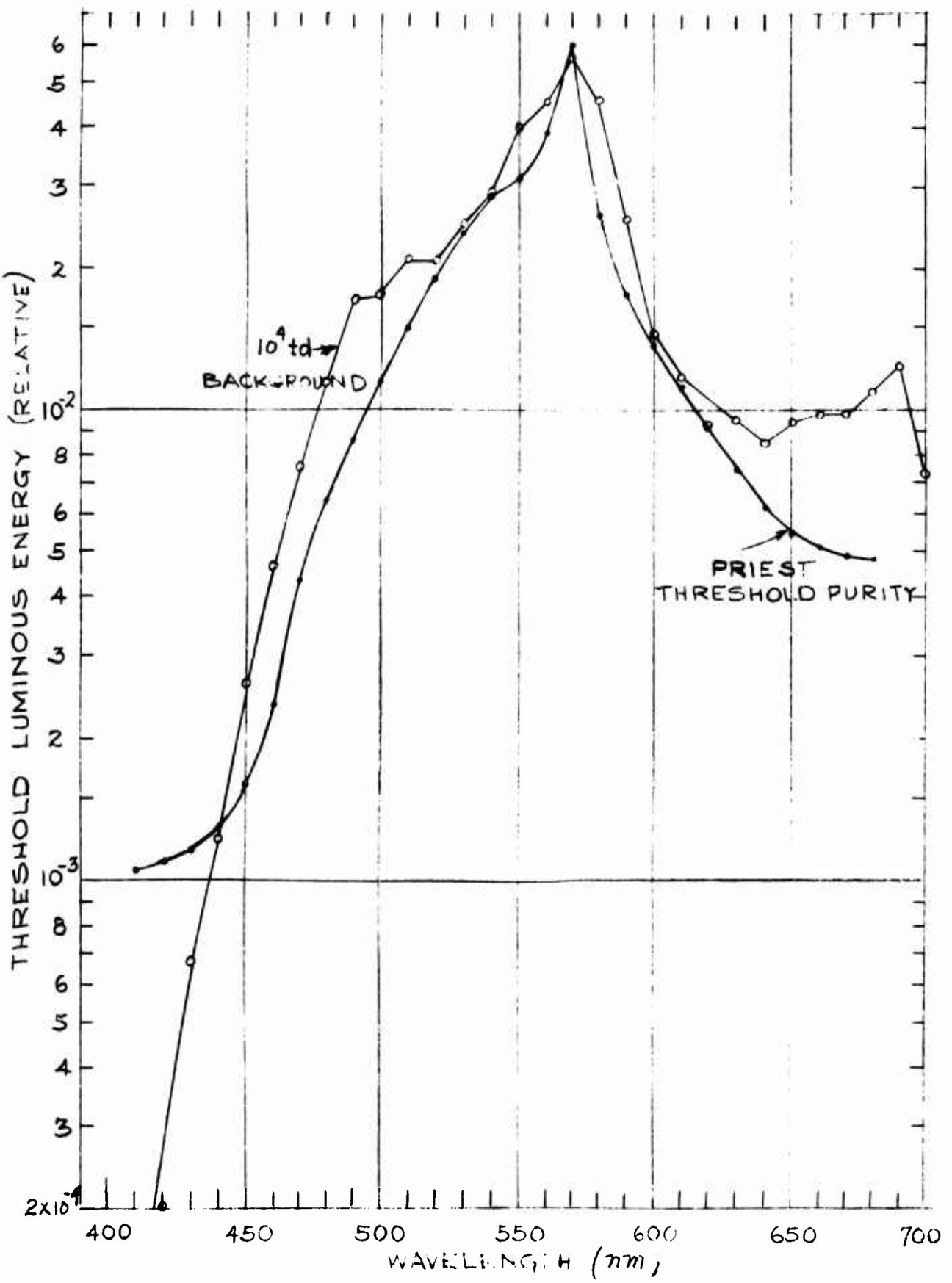

Figure 15. Comparison of the threshold purity curve from Priest and Brickwedde and the threshold luminous energy for monochromatic flashes superimposed on a 10^4 td white light background.

luminance of the test field was maintained constant at 15 mL and the surrounding field at 7.5 mL. Various filter combinations were employed to provide complementary hues in the central test field. A standard chromaticity was set in one half of the bipartite field and the pairs of complementary filters could be adjusted on the opposite half of the field for a match. The data resulted in a series of elipses on the ICI chromaticity diagram, each elipse indicating the standard deviation of matches for the various pairs of filter combinations used. The MacAdam elipses have become the basic unit for indicating color differences for specific color matching conditions.

In his 1942 paper MacAdam pointed out that the purity function could best be represented as an elipse centered about the illuminant point on the ICI diagram. Part of the data from Table V in his paper are reproduced in Table XIII of this report, comparing the first steps from white for IGP from the Priest paper and PGN, one of the subjects in MacAdam's experiment. Our mean results for VK and JS for the 10^4 td background have been transformed to the same form as the data from MacAdam's paper. This form is the log of the colorimetric purity at 570 nm divided by the colorimetric purity at the given wavelength. The values from Table XIII are shown plotted in Figure 16.

Table XIII. Comparisons of first steps from white for three different investigations. The values are log p_c (570 nm)/p_c λ

λ(nm)	IGP*	PGN**	JS & VK mean
400	1.75	2.20	2.94
10	2.75	----	2.75
20	1.73	----	2.45
30	1.72	----	1.92
40	1.66	1.83	1.66
50	1.57	1.59	1.34
60	1.40	1.48	1.08
70	1.14	1.05	0.87
80	0.97	0.72	0.70
90	0.84	0.58	0.52
500	0.71	0.55	0.50
10	0.60	0.52	0.43
20	0.49	0.49	0.43
30	0.39	0.42	0.35
40	0.31	0.35	0.29
50	0.28	0.25	0.15
60	0.18	0.14	0.10
70	0.00	0.00	0.00

Table XIII. (continued)

λ(nm)	IGP*	PGN**	JS & VK mean
80	0.36	0.15	0.09
90	0.52	0.39	0.35
600	0.63	0.56	0.58
10	0.72	0.69	0.68
20	0.82	0.77	0.78
30	0.90	0.82	0.77
40	0.98	0.85	0.82
50	1.03	0.87	0.78
60	1.06	0.88	0.76
70	1.08	0.89	0.76
80	1.08	0.89	0.71
90	----	0.89	0.65
700	----	0.90	0.89

* Reference 20
** Reference 21

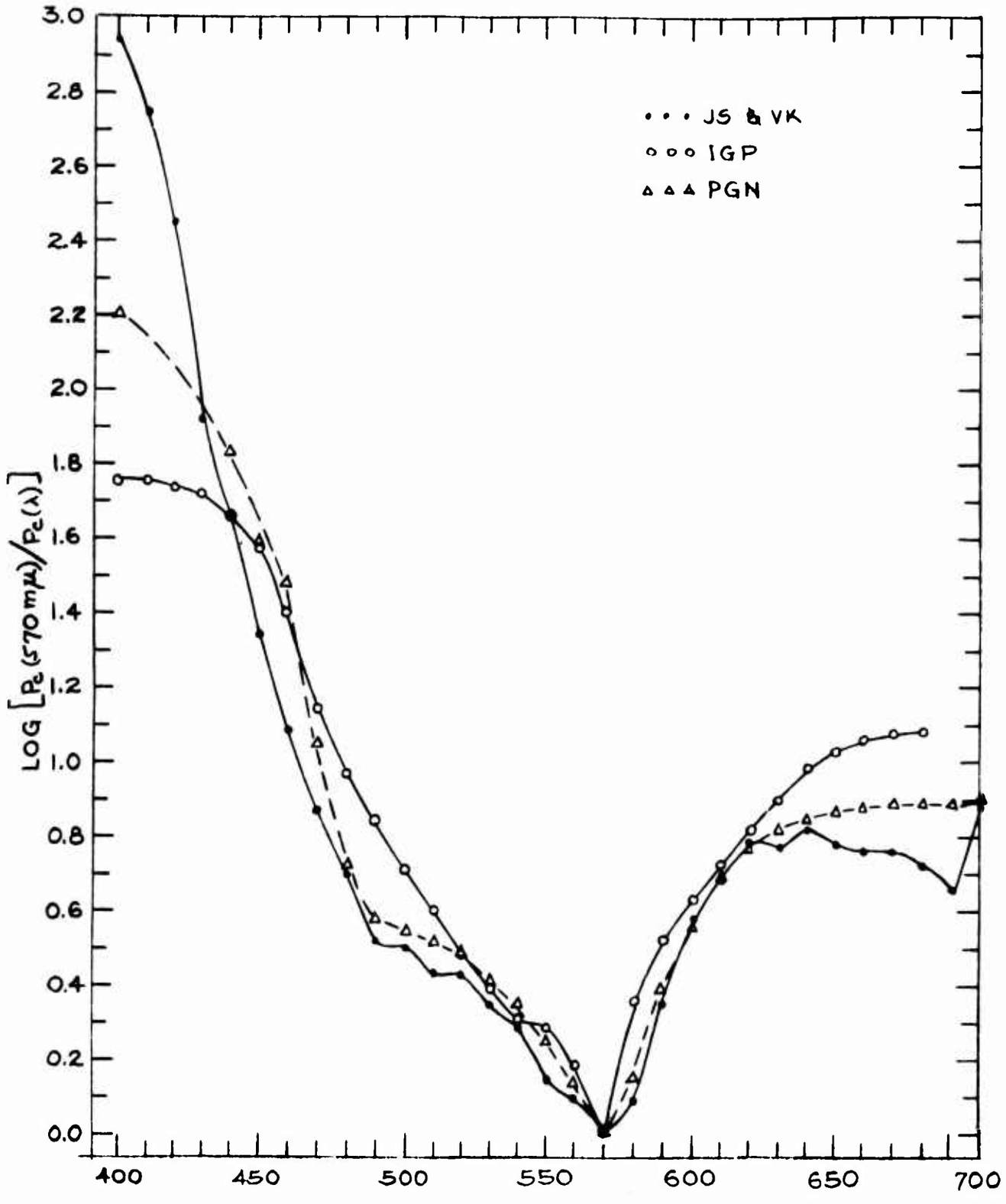

Figure 16. Comparison of the colorimetric purity threshold from three separate investigations using different techniques of measurement.

This curve is the inverse of that of Figure 15, but the agreement for the three separate determinations is even more impressive than for the comparison of Priest's and our data only. The data for PGN were obtained by measuring the excitation purity on the ICI chromaticity chart for the elipse produced around the illuminant point and then transforming to colorimetric purity.

The blue end of the graphs in Figure 16 show the greatest variation, with the curve from our data much higher than for the others. This means that the relative colorimetric purity for our subjects in the blue is considerably lower than for the other two subjects. It should be noted that the luminance of the test fields was measured directly in Priest's and MacAdam's experiments and was calculated from measured energy values in ours.

The chromaticity coordinates for the 10^4 td background were calculated using the standard tristimulus values of the 1931 Standard Observer and the distribution from Figure 10. The chromaticity points for each of the mean increment thresholds added to the white light background were also calculated. The results are shown in Figure 17. Instead of the perfect ellipses found by MacAdam with his technique, the data points follow an elliptical form over a wide range of the spectrum with a distinct distortion in the blue end.

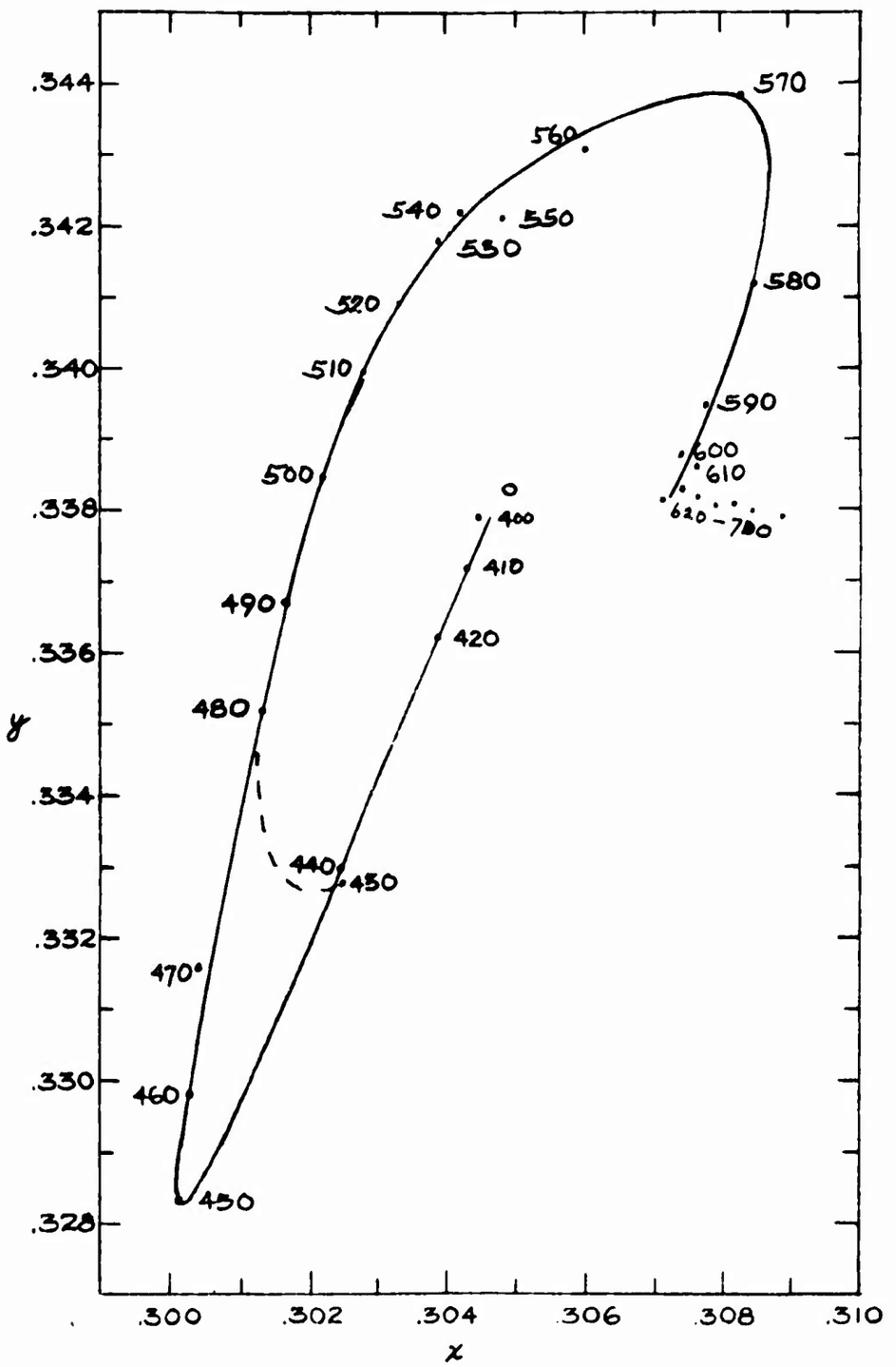

Figure 17. Chromaticity coordinates for each of the mean increment thresholds for the 10^4 td background.

7. CONCLUSIONS

The results are significant in that they point out the basic similarity of three distinctly different means of expressing chromatic sensitivity. The difference in the form of the chromaticity diagram for our results compared with MacAdam's may be due to difficulty in the calibration of the monochromatic test flashes at the blue end of the spectrum where the energy was extremely low. Or, it might have a more significant meaning in that the tristimulus values for the 1931 Standard Observer are suspect in the blue end of the spectrum. The long tail on our chromaticity diagram pointing toward the blue corner of the chromaticity chart could be an indication of erroneous values for the $\bar{Z}$ function of the tristimulus values.

There are distinct changes apparent in the chromatic sensitivity of the retina for different luminance levels of adaptation. The changes are great enough to provide a test at some future time of whether or not the afterimage following an intense flash of light will behave as an external field of the same subjective brightness and the same energy distribution as the flash. If the equality between the afterimage in an external field holds even for color sensitivity changes, the results could be important in indicating a type of color coding to decrease recovery times

following intense flashes. In view of Sperling's interpretation of the changes in color sensitivity as resulting from three basic mechanisms, it would also appear that protective goggles could be designed which would protect one or two of the basic color mechanisms from a flash leaving those mechanisms more sensitive to subsequent visual information.

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13. ABSTRACT

Three separate investigations into various areas of visual function at high levels of adaptation are reported. The reciprocity relationship between duration and intensity was studied for flashes of the order of 10^7 td·sec and for durations of 1.2 msec and 1.5 sec. There was approximately a 40% increase in recovery times for Sloan-Snellen test letters following the longer flashes.

The effect of varying the interval between two 250 mμ sec flashes on the subsequent recovery times was investigated. The interval between flashes was varied from zero to 1 msec in 100 μsec increments. The total integrated luminous energy in the flashes was of the order of 10^7 td·sec. There was a statistically significant change in recovery time with the interval between flashes at the 5% level. The 700 μsec interval resulted in an 18% increase in recovery compared with the zero interval for 630 mL targets. This is equivalent to more than doubling the energy in the zero interval or 500 μsec duration case.

In the third portion of the work, increment thresholds were measured for 45' monochromatic flashes superimposed on a 10° white light background of various illuminance levels from 10 td to 5×10^4 td. At the higher levels, marked notches appear in the sensitivity function at 570 mμ and 470 mμ as previously reported by Sperling. Analysis of the results show a striking similarity with the purity threshold curve and with MacAdam's ellipse for the white point of the chromaticity diagram.

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